

Experimental Study On Drilling Of Carbon Fibre Reinforced Plastics (CFRP)

A Dissertation submitted

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for the degree of**

**Master of Engineering
in
Production Engineering**

by

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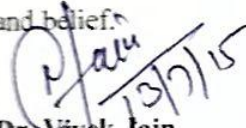
CERTIFICATE


I hereby declare that the thesis entitled "EXPERIMENTAL STUDY ON DRILLING OF CARBON FIBRE REINFORCED PLASTIC(CFRP)" is an authentic record of my work carried out as requirements for the award of degree of **Master of Engineering in Production Engineering** at **Thapar University, Patiala** under the supervision of **Dr Vivek Jain**, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala and **Dr Dheeraj Gupta**, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during 22 July 2013 to 15 July 2015. No part of matter embodied in this report has been submitted to any other University / Institute for award of degree.

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It is certified that the above statement made by the student is correct to the best of our knowledge and belief.


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DEDICATED TO MY FAMILY

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Abstract

In this research, study has been made to investigate the effect tool design and machining parameters on the drilled hole quality considering the output factors as drilling induced delamination, diameter deviation and surface roughness on drilling of Carbon fibre reinforced plastics. Input factors considered are tool type (viz. twist drill, brad point drill and end mill), spindle speed (viz 800 rpm, 1000 rpm, 1200 rpm) and feed rate (viz 10 mm/min, 15 mm/min, 20 mm/min) all varied at three levels and fourth factor as coolant (on, off) varied at two levels. Mixed L18 orthogonal array was used to perform the experiments. One replication for each of experiment was performed. Factors affecting the mean value of output have been found using ANOVA (analysis of variance) and their optimum levels have been specified and those influencing the variation have been found using S/N (Signal to Noise ratio).

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Chapter 1

Introduction

1.1 Introduction

Carbon fibres are readily utilized these days at a larger extent, therefore automatic production is under severe competition to increase productivity due to spiral increase in demand of carbon fibres. Carbon fibre has desirable mechanical properties i.e. it can possess high strength than steel, high stiffness than titanium and lighter in weight than aluminium.

Due to increase in material use in different areas, it is getting increasingly complicated to machine therefore challenge on function of cutting tool and its performance has increased and much attention is therefore on edge and hole quality.

1.2 Carbon Fibre Reinforced Plastics

Carbon fibres are manufactured by orienting the crystals of graphite in direction of fibres and are used at large scale as reinforcements in modern times. Carbon fibre consists of tremendously thin fibres varying in size from 0.005–0.010 mm in diameter which are consists mainly of Carbon atoms. The orientation of crystals makes the fibre highly strong as compared to its size. Carbon fibre are being used extensively in critical components of airplanes due to its light weight, which directly helps in reducing fuel consumption, leads to reduction in harmful gaseous emissions and thus increase in load carrying capacity. Several thousand of Carbon fibres are twirled into a form of thread, which can be used in same form or can be woven into a Fabric.

The polymer used as binder is mostly a thermoset resin such as epoxy, while other thermoset or thermoplastic polymers like nylon, vinyl ester, polyester can also be used. The composite material in addition to carbon fibre may contain other fibres like aluminium, glass fibres, Kevlar. The type of additives used in the binding of matrix (the resin) affects the properties of the final CFRP product. Frequently used additives are silica, rubber. CFRPs are commonly used in bicycle components, manufacture of bicycles, the transportation industry; boats and trains, normally in cars, sporting goods industry and in fishing rods and golfing equipment.

Though carbon fibre is expensive, due to high strength to weight ratio, it has many applications in automotive fields and aerospace, for example in formula one racing and where rigidity is required like in rowing shell and sailing boats, motorcycles and top-end bicycles. CFRP is increasingly becoming common in small consumer that require stiffness, lightness and strength due to improvement in manufacturing techniques and costs such as in: laptop bodies, racquet frames ,tripod legs, stringed instrument bodies, tent poles, shells of drums, fishing rods, golf clubs, hockey sticks, billiards cues, crash helmets and bows and arrows.

1.2.1 Properties

Carbon-fibre-reinforced plastics are composite materials. The composite consists of two parts: matrix and reinforcement. In CFRP strength is provided by the reinforcement which is carbon fibre. The matrix is usually a polymer, used as binder to keep the reinforcements together, such as epoxy. As CFRP consists of two different elements, the properties of material is dependent on these two elements.

The reinforcement gives the CFRP strength and rigidity, which is calculated by elastic modulus, CFRP has directional strength properties contrasting isotropic materials like aluminium and steel etc. The properties of CFRP are dependent on fraction of the carbon fibres relative to the polymer and layouts of the carbon fibre.

Carbon Fibre has much higher tensile strength, tensile modulus, flexural strength, flexural modulus, high compressive strength, high compressive modulus, and much higher inter laminar shear strength, plane shear strength, low thermal expansion and high fatigue resistance.

Even if CFRP possesses high initial strength-to-weight ratio, major drawback of CFRP in designing of parts is due to lack of definable fatigue endurance limit, meaning that the properties of fatigue failure CFRP are difficult to calculate and thus designing becomes complicated. Due to this, when critical cyclic-loading applications are applied to CFRP, designers in order to give sufficient reliability of component over its service period, design in significant strength safety margins.

1.2.2 Fiber Orientation and Structure

Unidirectional reinforcement (UD), is one in which highest stiffness and strength is obtained in the fibre direction alignment.

Properties:

- maximum strength in the fibre direction alignment.
- bad handling features.
- Subjected to high risk of delamination during critical machining.

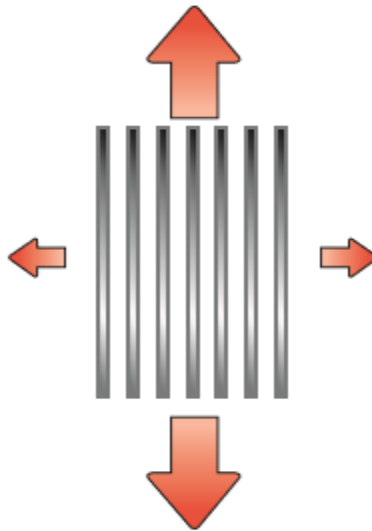


Figure 1.1 Unidirectional layout¹

Two-dimensional woven fabric

In two dimensional woven fabric fibres are oriented along both sides to sheet thereby providing uniform strength in both directions.

Properties:

- identical strength in each directions
- better handling features
- Risk of delamination is comparatively lower

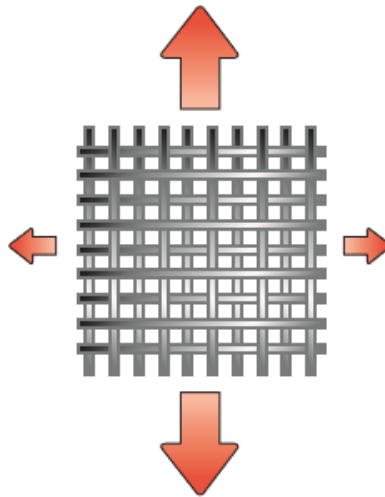


Figure 1.2 Two dimensional woven fabric¹

1.2.3 Manufacturing

The methods by which most carbon-fibre-reinforced plastics are made vary, depending on the piece being created, number of these particular pieces going to be created and finish (outside gloss) required. The choice of matrix used has much significant effect on the properties of the end finished CFRP.

The chief element of CFRP is a fibre. A unidirectional sheet is created from these carbon fibres. These unidirectional sheets are placed one on another in a quasi-isotropic layup, e.g. 0° , $+90^\circ$ or -90° relative to each other. A bidirectional woven sheet is created, i.e. a twill with 2/2 weave from the elementary fibre. Many CFRP parts are created with a single layer of carbon fabric that is backed with fibreglass. Chopper gun is tool used to create the composite parts quickly. Thin shell is created using carbon fibre. After this chopper gun cuts rolls of fibreglass into short lengths while resin is sprayed at the same time, resulting in mixture of resin and fibreglass on the spot. The resin is either internal mixed, requiring cleaning after every use or externally mixed, wherein the hardener and resin are sprayed separately.

Manufacturing methods may include the following

1. Molding
2. Vaccum bagging
3. Compression molding

4. Filament winding

Moulding

Layering carbon fibre sheets into a mould in the shape and design of the final product to be obtained is one method of producing CFRP. The weave and alignment of the carbon fibres is chosen according to properties such as strength and stiffness of the desired material. After that epoxy is poured into the mould is heated or air-cured. The produced part is stiff, strong as compared to its weight and it is also corrosion resistant. Parts to be used in less vital areas of use are manufactured by wrapping cloth over the mould. Then epoxy either painted on fibres or preimpregnated into the fibres (also known as prepreg).

Vaccum Bagging

High-performance parts are vacuum-bagged or autoclave -cured, because presence of even small air bubbles in the material reduces its strength. A carbon fibre is polished and waxed. Then a release agent is applied before fabric and resin are applied. After this vacuum is created and pulled and set aside for some time thereby allowing the piece to be cured (harden).

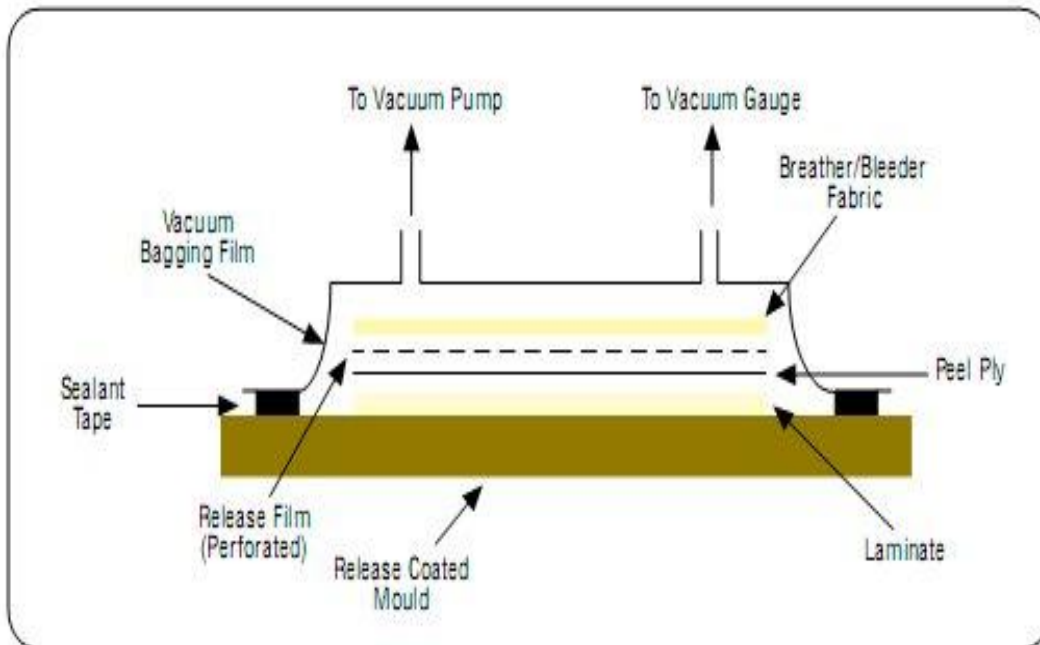


Figure 1.3 Vaccum bagging process²

Two ways of applying resin to fabric to a vacuum mould.

1. Wet layup
2. Dry layup

1. Wet layup

In wet layup the two-part are mixed and resin is applied after which it is placed in the mould and placed in the vacuum bag.

2. Dry layup

In this method the carbon fibre material is impregnated already with resin (pre-preg) and is applied to the mould in a similar way as to adhesive film. The assembly is then cured by placing it in vacuum. With dry layup method lighter constructions are achieved than wet layup and resin wastage is least in this case. Due to higher concentration of resin in wet layup methods resin is more difficult to bleed out.

Compression Moulding

Compression moulding is a quicker method. It is a two-piece (consisting of male and female) mould made usually of aluminum or fibreglass that is closed and bolted together with the resin and fabric between the two. Once it is bolted together, it is comparatively clean and is therefore stored easily without a vacuum until after curing or moved around. However, the moulds requires lot of material and high pressure to hold together.

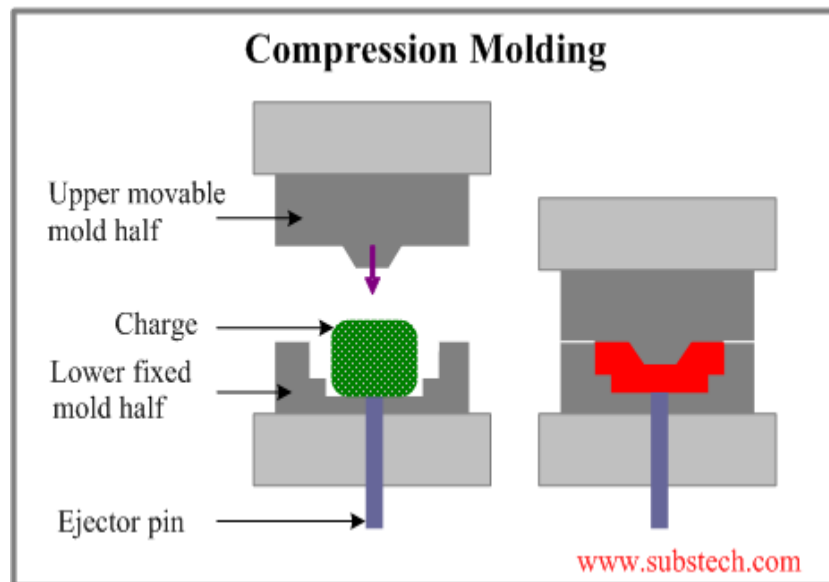


Figure 1.4 Compression moulding²

Filament Winding

It is used for complex and intricate shapes. A filament winder is manufacture CFRP parts by winding filaments around mandrel or core.

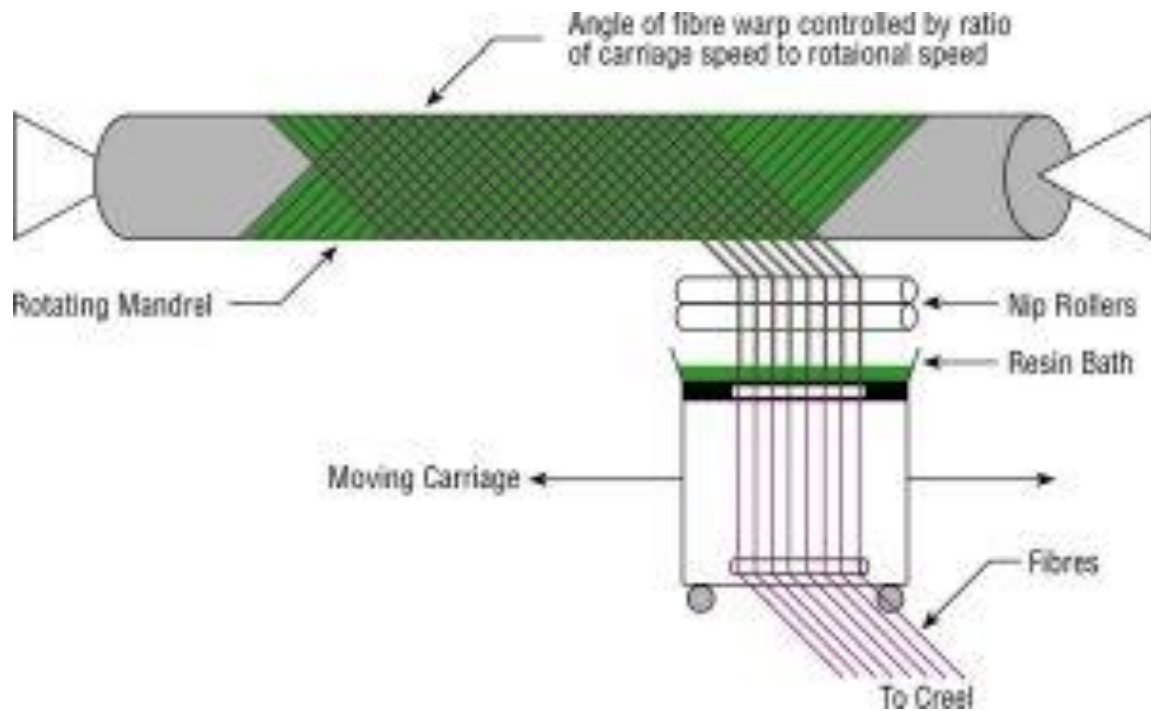


Figure 1.5 Filament winding²

1.2.4 Applications

1. Aerospace engineering
2. Automotive engineering
3. Sports goods
4. Other applications
 - Laptop cases
 - Audio components
 - Consumer items such as knife handles.
 - Musical instruments

1.2 Drilling

1.2.1 Introduction

Drilling is a manufacturing process that makes use of drill bit to enlarge or cut a circular cross section holes in materials. The drill bit is a multipoint rotary cutting tool. The drill bit is revolved at different rates varying from few hundreds to thousands of revolutions while being pressed against the work. This presses the cutting edge against the work which pulls out chips from the hole as drilling is being done. There is presence of sharp edge on the entrance side and burrs on the exit side of drilled hole. The hole surface inside mostly has feed marks which are helical in shape. Drilling also affects the mechanical properties of the work due to creation of a very thin layer of highly disturbed and stressed material on the newly formed surface of hole and low residual stress around the hole opening. This makes the workpiece to become more prone to corrosion and crack propagation at the stressed surface. A finishing operation is often done to prevent these critical conditions. For fluted drill bits, chips are removed from flutes. Depending upon the process parameters and material, chips may form a number of small flake or long spirals. The chip type formed is an estimate of machinability of material. Long chips suggest poor material machinability. Cutting fluid is a kind of lubricant and coolant designed specifically for metal working and machining processes. There are different types of cutting fluids, which include aerosols (mists), gases, oils, gels, pastes, oil-water emulsions air. They may be made from animal fats, petroleum distillates, water, and air, or other raw ingredients. Drill is an end point cutting tool which possess one or added helical or straight in shape flutes. Few drills have a hollow body for the easy movement of cutting fluid and chips during the production of a hole in the work. Drills vary broadly in shape, tolerance and aspect. Drills are categorised according to their lengths, the material used, shapes, characteristics of point, number of flutes, size series and style of shank. The type of drill for a given operation to be performed depends on its structural characteristics, if the material to be drilled is solid or cored, the hole dimensions, whether a blind or through hole is required and cutting conditions and characteristics of the machine tool and fixture. Selecting the proper type of drill for drilling operation requires all these factors to be taken into account.

1.2.2 Conventional point or twist point

Conventional point or twist point drill is the most frequently used type of drill point ground on standard, 118 degree point angle. The chisel edge is either two faceted (which results in a flat or blunt chisel) or conventional (with conical relief) and has a high negative rake angle (-50° to -60°). Conventional drills often require a centering hole as they tend to “walk” or drift during entry. They are mostly used in operations that do not require high production rates or high precision. The conical point can be ground to provide a small round off 0.08 to 0.19 mm depending upon diameter of drill along the chisel edge, which results in significant improvement in the centering characteristics and chisel edge cutting action.

1.2.3 Brad point drill

Brad point has a slightly concave main lips and web is thinned at center point ground on an acute point angle which is usually 90° and less than 120°. The function of outer corner is to act as trepanning tool. The length of center point is mostly 20% to 30% of the drill diameter. Brad point is used mainly for drilling accurate, holes of round shapes in sheet metals with minimum formation of burrs. A slug or disk of material is formed at exit.

1.2.4 End mill

An end mill is a milling cutter type used as a cutting tool in milling applications in industries. It is differentiated from the drill bit in its geometry, manufacture and application. A milling bit can generally cut in all directions while a drill bit can only cut in the axial direction.

Chapter 2

Literature Review And Problem Formulation

2.1 Literature Review

Mayuet et al(2013)⁴ studied the Tool wear and Work piece wear using uncoated WC-Co drills while machining of CFRP and concluded that Tool wear-Wear remains constant during cutting process, high temp melts epoxy matrix and results in resin deposition along drill flutes. W/P wear- Delamination takes place when axial forces are very high and by cracks caused by fatigue due to low speed impacts. Max Break in/out obtained at lowest cutting speed and feed.

Shyha et al(2010)⁵ studied Thrust force, Torque and Delamination while drilling CFRP plate(3mm thick) using WC stepped drill while varying Drill feed rate Prepreg form and found that effect of prepreg form on tool life was evident while operating at higher feed rate. Delamination factor at hole exit ranged b/w 1-2.1 and b/w 1.2-1.8 at hole entry. Holes obtained were found to be undersize.

Teicher et al(2013)⁶ studied the effect of Pulse energy, Discharge current, Circuit voltage on Electrode wear, MRR, Surface roughness, Thermal damage while performing Micro EDM of CFRP and found that Increasing pulse energy-High MRR, high tool wear, high surface roughness. Constant pulse energy-On increasing current it damages and burns matrix. Low pulse energy-Less MRR, high surface finish OCV has least impact on above parameters, should be between 90V to 130 V. Thermal damage-Adjustment in discharge current and OCV is crucial in determining size of HAZ and degree of delamination.

Jenarthanan et al(2012)⁷ studied the effect of Cutting speed, Feed rate, Depth of cut while machining of CRFP using Solid carbide end mill coated with PCD and obtained optimum values of variables by regression eqn

Zhang(2003)⁸ studied grindability of multidirectional CFRP and found Grinding force, Chip formation, Surface roughness. Results suggest that Grinding force has a linear increase with increasing depth of grinding. Chips produced contain a mixture of broken fibres of varying

lengths and fine powder particles. Longitudinal surface roughness varied strongly with local fibre orientation. Severe fibre pull out was seen with plies of -45 deg.

Romoli et al(2011)⁹ studied UV laser drilling of PEEK reinforced with carbon fibres. The behaviour Input power, Pulse Overlap, Scanning speed were varied and results suggest that Avg power has parabolic behaviour in range(70-110KHz) with max point for 90 KHz, Pulse overlap >>75% induce thermal affection (swelling of fibres). Drilling of thick laminates (>1 mm) MRR optimized by removing complete layers of material. Heat affection zone (HAZ) is reduced by spacing the circular grooves instead of overlap.

Qiang et al(2014)¹⁰ studied the Impact responses and residual flexural properties of narrow CFRP laminates by performing Impact test, Three point bending test and found that: Damage mode - Matrix cracking in low impact energy, Delamination in Middle impact energy and Complete breakage was observed in higher impact energy range, Greatest degradation of normalized flexural strength and flexural modulus is in middle energy region.

Tsao et al(2011)¹¹ studied the effect of drilling parameters on thrust force in drilling CFRP using compound core special drills and found that Cutting velocity ratio, feed rate, inner drill dia are parameters influencing thrust force. Compound core drills produce lower thrust force, delaminations, chip clogging and high chip removal as compared to core drill. High negative cutting velocity ratio and low feed rate produce low thrust force

Wolfgang et al(2011)¹² studied the Occurrence and propagation of delamination during m/cing of CFRP with slot mill by varying the Fibre orientation, Cutting edge angle. It was found that Occurrence of delamination and fibre overhang depends on tool wear and fibre orientation angle. Even with worn out tool in cutting angle range 0-90 deg no delamination takes place. In critical range (cutting angle 90-180 deg) delamination and overhang is seen. Top layer delamination depends on cutting angle and not on fibre orientation angle.

Davim et al(2004)¹³ studied damage and dimensional precision on milling CFRP using two flute cemented carbide end mil, six flute cemented carbide end mill and two other factors: Cutting velocity, feed rate. It was observed that Value of surface roughness increases with feed rate, decreases with cutting velocity. Two flute end mill provides better surface finish than six flute end mill. Feed rate has significant effect on surface roughness. Delamination

factor increases slightly with feed rate. Delamination factor for two flute end mill is small than six flute end mill.

Zern et al(2007)¹⁴ studied the crack evolution on atomistic scale during pyrolysis of CFRP by liquid silicon infiltration process. Crack formation, Crack mechanism, Crack propagation were studied and it was observed that substantial cracking occurs beyond 650 deg C. Crack development started at pores that develop as a compensation for rough fibre surface. Propagation of crack takes place by progress of new nanoscopic cracks caused due to debonding of fibre matrix in tensile stress field in front of crack tip and leading to connection with main crack.

Yigit karpat(2013)¹⁵ formulated force modeling for milling of CFRP with double helix tool Milling was performed using diamond coated carbide helix end mill and Milling force torque, diamond coating wear were studied and it was concluded that in Unidirectional CFRP-Single helix mill. Force in Z direction small as compared in XY direction. Radial forces are larger than tangential forces. In bidirectional CFRP-Double helix mill No. of teeth can be increased to maintain constant chip thickness. Abrasive nature of carbon fibres fractures diamond coating on tool, increasing the milling forces.

Ferreira et al(2000)¹⁶ studied the effect of tool material(Cemented carbide, Ceramics, Diamond PCD, CBN and cutting speed on Tool wear, feed force, surface roughness. It was observed that cutting speed has greatest influence on tool life of carbide tool. Tool wear has influence on feed force and surface roughness. Diamond tools are most effective for finishing operations

Krishnaraj et al(2012)¹⁷ optimised m/cing parameters at high speed drilling of CFRP using K20 carbide drill. Cutting speed and feed rate were factors under investigation. Hole diameter, circularity, peel up Delamination, push out delamination, thrust force and torque were the output factors which were obtained and results concluded that feed rate has significant effect on push out delamination, thrust force and also on diameter of hole. Lower feed rate reduces push out delamination and thrust force. Higher feed rate results in inaccurate hole diameter. Spindle speed is major determinant of circularity of hole. Peel up Delamination was less as compared to Push out delamination.

Liu Jing et al(2011)¹⁸ observed the feasibility study of rotary ultrasonic elliptical machining of CFRP using Nickel bonded diamond core drill. Chip removal, tool wear, hole precision, material removal rate, cutting force, exit delamination and surface roughness were studied and results concluded that RUEM has better chip removal, removal of excess heat than conventional drill. RUEM reduces tool wear. RUEM improves precision of holes. RUEM prevents delamination at exit of hole and improves surface quality. RUEM reduces average cutting forces and torque.

Dold et al(2012)¹⁹ made comparison of ground and laser machined PCD tools in cutting CFRP. Surface roughness on flank and rake face, cutting forces, tool wear, surface roughness of W/P were the observed values. It was concluded that laser treated cutting edges have cut diamond grains and exhibit a homogenous surface. Ground tools tend to have broken out grains. Grains are torn out of surface leaving holes in binding material during grinding. Tool wear is same on both ground and laser machined PCD tools. Feed force shows good correlation to increasing tool wear. Surface roughness is independent of increasing wear. Ground tool shows grooves in cutting direction.

Hocheng et al(1993)²⁰ performed the preliminary study on milling of unidirectional CFRP using solid carbide end mill. Chip form, cutting mechanism and cutting force were the output responses which were studied and the results concluded that Cutting mechanism involves fracture rather than plastic deformation. Serious burrs are formed when fibres are not cut successfully. Milled surface parallel to laminate is smooth. Cutting forces are higher in vertical direction

Tsao et. al. (2007)²¹ studied if tool wear has significant effect on delamination of drilling composite materials. The experimental results demonstrate that there is high critical thrust force with increase in wear ratio.

Vaibhav et al(2012)²² compared the experimental and numerical investigations in conventional and ultrasonic assisted drilling of CFRP. HSS drill bit(dia 6 mm),Piezoelectric transducer were used. Feed rate, vib frequency were the variable parameters. Results depicted that thrust force was less in CD as compared with UAD. With increase in rotational speed thrust force in CD decreased. With increase in rotational speed thrust force in UAD

decreased but rate of decrease was higher than CD. Avg thrust force reduction was about 30% . FEM model-Thrust force magnitude matches with actual experiment.

Hatsukade et al(2002)²³ studied the Detection of internal cracks and delamination in CFRP using SQUID-NDI system using DC current injection method. Results depicted that downwards peak above centre parts of slots are response to slots in Gradient of vertical mag field Vs X axis. Amplitude of response decreases exponentially as depth increases. Mag field response to slots upto 15mm depth was detected.

Islam Shyha(2013)²⁴ investigated into CO2 laser trimming of CFRP GFRP composites. Cutting speed, laser beam power, gas pressure were the input parameters and MRR, surface roughness, kerf width and charring/fibre pull out were the output parameters. It was observed that MRR for GFRP is Greater than CFRP due to lower melting temp of glass. Gas pressure and cutting power has very limited effect on MRR. Higher cutting speed increases surface roughness. Premature charring of matrix less dominant especially CFRP. Kerf width is greater at cut entry due to limited variation b/w laser beam size.

Fujita et al(2013)²⁵ studied microm/cing of CFRP with ultra short laser pulses using Ti Sapphire laser. It was observed that between two slits (pitch 500 micrometer)CFRP remained almost intact. Less than 30 micrometer slit width on 100 micrometer thick CFRP is possible.

Cong et al(2011)²⁶ performed rotary ultrasonic machining of CFRP using cold air as coolant using metal-bonded diamond core drills. Tool rotation speed, feedrate, ultrasonic power, cold air pressure were the input parameters and burning, delamination and tool blockage were studied to obtain the following results. Higher cold air pressure led to increase in feasible regions of machining. When tool rotation speed was very low (≤ 2000 rpm) irrespective of the levels of ultrasonic power and feed rate, dry machining was not feasible. Dry machining was not feasible when high ultrasonic power combined with low feedrate (≤ 0.7 mm/s).

Hocheng and Tsao(2006)²⁷, conducted experiments to support the advantages of using special drills over twist drills. Four special geometries of drills were used. Drills that were used include, candle stick drill, saw drill, and step drill made of HSS (10mm diameter) .They have reported that drill geometry and feed rate have significant effect on thrust force. The

tangential force decreases with increase in point angle due to increase in the tool orthogonal rake angle with increase in point angle.

Piquet et al. (2000)²⁸ performed drilling on thin carbon/epoxy laminates with two different types of drills, a special geometry drill and a helical drill and reported that both drills lead to a damage at the hole wall at entrance and at the hole exit. Drilling with drill of special geometry shows a considerable reduction in the final damage on CFRP.

Luis M. Durao et al. (2009)²⁹ performed drilling of carbon fibre laminates using different drill geometries and cutting parameters. The motive of study was to minimise delamination. Thrust forces while drilling and delamination were measured using radiography, image processing and analysis computational techniques. The parameters setting that gave minimum value of delamination and thrust force was cutting speed of 53 m/min and feed rate of 0.025 mm/rev. Reduction in thrust force was about 35% for cutting speed and 12% for feed rate and delamination reduced about 4%- 5% when these combinations of machining parameters were used.

C.C. Tsao et al.(2007)³⁰ concluded that spindle speed and feed rate are the critical factors that influence the thrust force and delamination among the three control factors (diameter ratio, feed rate, and spindle speed) used in the study. The diameter ratio was having insignificant effect. A small feed rate produced low thrust force in drilling, which decreased the extent of induced delamination.

DeFu Liu et al.(2012)³¹ studied the mechanical drilling on composite laminates including the drilling operations (grinding drilling ,conventional drilling, high speed drilling and vibration-assisted twist drilling), drill bit geometry (twist drill bit, brad drill bit, step drill bit, straight-flute drill bit, core drill bit) and materials, drilling- induced delamination and thrust force, tool wear approaches to reduce delamination. Feed rate was the largest contributor to tool wear, delamination and thrust force while drilling of composite laminate. Minimum drilling induced delamination and high tool life was observed while machining with low feed rate and using high cutting speed.

C.C. Tsao and H Hocheng (2007)³² studied the effect of feed rate, spindle speed, thickness of core drill and grit size of diamond on thrust force while machining of CFRP using core drill.

Experiment accomplished that reduction in thickness of core drill, medium spindle speed, large grit size, low feed rate lead to a reduction in thrust force. Grit size of diamond is the major important factor.

Bandhu et al(2014)³³ obtained the optimum value of torque, thrust force, surface roughness and delamination factor while drilling of CFRP. Experiments performed using three drills of different materials(HSS, carbide and PCD coated drill) varied at three levels of point angle, speed and feed. It was concluded that low thrust force, good surface finish and lower delamination was achieved while using low point angle, low feed rate and high spindle speed. On other hand high spindle speed and lower feed rate led to lower torque.

Literature Analysis

Types of drilling operations performed on CFRP

- **Conventional methods**
 - 1 Conventional drilling
 - 2 Grinding drilling
 - 3 Vibration assisted twist drilling(VATD)
 - 4 High speed drilling
- **Unconventional m/cing methods**
 - 1 Laser machining
 - 2 Abrasive water jet machining
 - 3 Electric discharge machining
 - 4 Ultrasonic machining

Conventional methods

- **Delamination**

Conventional drilling

- Delamination increased with increase in cutting speed
- Delamination tendency increased with increase of point angle of twist drill bit(tool cemented carbide)

High speed drilling

- Delamination tendency decreased with cutting speed
- With increase in point angle of drill bit delamination tendency increased
- More promising than conventional drilling

Vibration assisted twist drilling(VATD)

- Decrease in delamination as compared to CD due to decrease in thrust force
- Several empirical models developed to correlate delamination with input variables(speed,feed,diameter of drill,point angle)
- Effect of feed rate is more than that of cutting speed for delamination
- **Thrust force**
- Below critical thrust force no delamination occurs
- Linear elastic fracture mechanics method used to calculate critical thrust force
- Model suggests thrust force as concentrated load at centre
- Above model modified by assuming thrust force as UDL

Effect of input variables

- Cutting speed has insignificant effect on thrust force
- Thrust force increases with increase in point angle of drill
- Lower thrust force was observed using brad point drill bits and stepped drill bits than standard twist drill and slot drill
- Thrust force increases with tool wear
- Thrust force in VATD was less 20-30% than conventional drilling
- Use of predrilled pilot holes reduce thrust force due to chisel edge(40% of total force when low feed rate and 60% at high feed rate)
- **Tool wear**

Types of wear mechanism

- Abrasive wear

- Wear by chipping
- Adhesion wear

Tool wear was not uniform and divided into three regions

- Initial wear region caused by chipping
- Secondary wear region by abrasive wear
- Tertiary(severe)wear region by carbon adhesion on flank face

Effect of input variables

- Tool wear of HSS bits occurred more rapidly than cemented carbide drill bits
- Straight flute drill bit has lowest flank wear in CD and in VATD
- Wear increases as cutting speed and feed is increased

Unconventional methods

- **Abrasive water jet machining**

Kerf angle

- As the speed increases kerf angle increases
- For same speed as angle of turning decreases kerf angle increases

Surface roughness

- At very low cutting speed WJM show larger Ra value than AWJM
- Though good results were obtained from WJM at very low speed it increases
- Therefore by decreasing speed of AWJM it would decrease kerf angle and decreases surface roughness
- Delamination for AWJM was low than WJM marginally

- **Laser Machining**

- At top surface width was narrow which increases as depth increases resulting in larger width at bottom
- As speed increases kerf angle decreases

Surface roughness

- Surface roughness cannot be measured as laser burnt the surface on both sides
- Optimum power used to ensure through cut. High power results in burning of matrix(thermal damage)
- **Electric discharge machining**
- Thermal damage-Adjustment in discharge current and OCV is crucial in determining size of HAZ and degree of delamination
- Increasing pulse energy-High MRR, high tool wear, high surface roughness
- Constant pulse energy-On increasing current it damages and burns matrix
- Low pulse energy-Less MRR, high surface finish
- Open circuit voltage has least impact on above parameters
- **Ultrasonic Machining**
- RUEM has better chip removal,removal of excess heat than conventional drill
- RUEM reduces tool wear
- RUEM improves precision of holes
- RUEM prevents delamination at exit of hole and improves surface quality
- RUEM reduces average cutting forces and torque
- Using cold air as coolant
 - Higher cold air pressure led to larger feasible regions.
 - Dry machining was not feasible when tool rotation speed was too low (≤ 2000 rpm) regardless of what levels of feedrate and ultrasonic power.
 - Dry machining was not feasible with high ultrasonic power combined with low feedrate.

2.2 Literature Gap

Carbon fiber reinforced plastic (CFRP) composites have strong carbon fibres surrounded by a weaker plastic matrix. The fibers are to support the load. The matrix serves to distribute, hold, and protect the fibres and also to transmit the load to the fibres. From the literature survey, research work has been done drilling of CFRP using conventional drilling, grinding drilling, vibration assisted drilling, milling, high speed drilling. It has been found that majority of research work has been done to investigate roughness, defects and their propagation, determination of optimum machining parameters to reduce failure occurring during drilling in composites. However major area of interest has been improving upon the hole surface quality, reducing thrust force and delamination and achieving accurate dimensional accuracy by varying the machine parameters viz spindle speed, feed rate, cutting speed, drill diameter with a drill of prescribed geometry. It has been found that work regarding the effect of tool design (twist drill type, brad point drill type and end mill) on improving of hole output and machining parameters has not been reported much. In addition to it the effect of coolant on the hole characteristics (surface roughness, exit and entry delamination factor and dimensional deviation) has not been investigated.

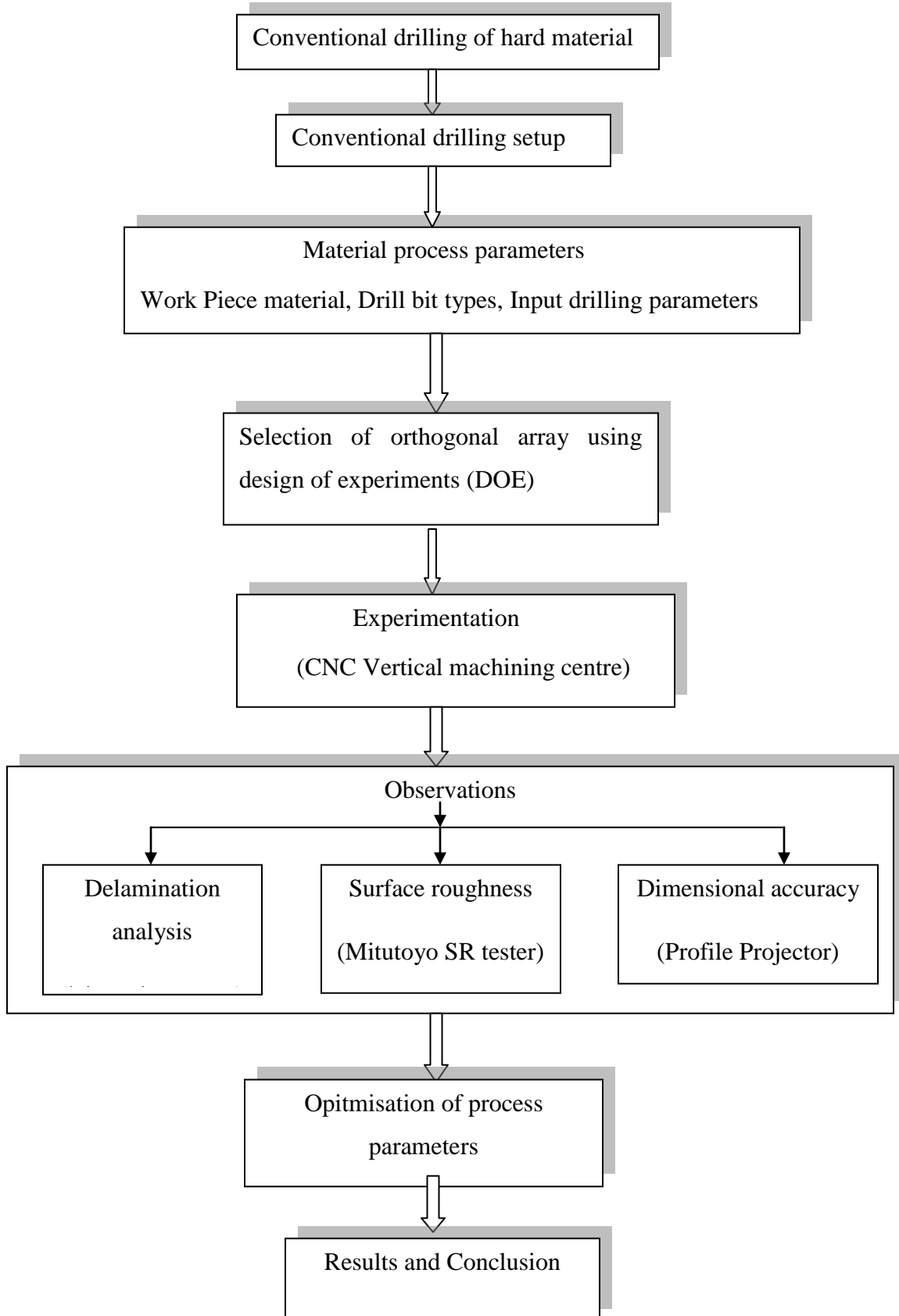
2.3 Problem Formulation

Study has been made to investigate the effect tool design and machining parameters on the drilling induced delamination, diameter deviation and surface roughness on drilling of Carbon fibre reinforced plastics.

2.4 Objectives

- To study the effect of tool design on the drilling induced delamination, dimensional accuracy and surface roughness on drilling of Carbon fibre reinforced plastics.
- To study the effect of spindle speed, feed rate on hole quality on drilling of Carbon fibre reinforced plastics.
- To study the effect of coolant on output parameters on drilling of Carbon fibre reinforced plastics.
- To achieve optimum values of drilling parameters and tool type.

2.5 Work Plan



Chapter 3

Experimental Setup

3.1 Process parameters

Four factors have been identified as process parameters, viz. spindle speed, feed rate, coolant and drill type. Spindle speed, feed rate, drill type are each varied at three levels while coolant is at two levels

3.1.1 Spindle speed

Literature survey shows that spindle speed has been varied between 500 rpm to upto 5,000 rpm. It has been seen that C.C.Tsao³² and Hocheng and Tsao³⁰ have performed experiments at spindle speed 800 rpm, 1000 rpm, 1200 rpm using core saw drill and core drill respectively and concluded that delamination varies considerably between 800 rpm and 1400 rpm. Therefore spindle speed is set at three levels viz. 800 rpm, 1000 rpm, 1200 rpm.

3.1.2 Feed rate

C.C. Tsao, Y.C. Chiu¹¹ have reported the variation in delamination and surface roughness in CFRP in between the feed rates at 10 mm/min, 15 mm/min, 20 mm/min using compound core special drills. Feed rate has been set at three levels viz 10 mm/min, 15 mm/min, 20 mm/min.

3.1.3 Coolant

Coolant is set at two levels viz. on, off. Coolant used was soluble oil water emulsion and mode used was jet type.

3.1.4 Tool type

The research was carried out using three types of bits viz. twist drill bit, brad point drill bit and six flute end mill. Diameter is kept constant at 8mm. Effect of drill design on output parameters was studied using this factor.

Input Parameters

- Coolant: ON, OFF
- Tool type: twist drill bit, brad point drill bit and six flute end mill
- Spindle speed: 800 rpm, 1000 rpm, 1200 rpm
- Feed Rate: 10 mm/min, 15 mm/min, 20 mm/min.

3.2 Output Parameters

3.2.1 Delamination Factor

Delamination is one of the major problems that encountered in drilling of composite laminates as compared to that of metals. It is commonly regarded as failure dominated by resin or matrix. It generally appears as peeling away of the lower plies or ply and is credited to the thrust provided by drill thereby pushing the layers apart rather than cutting through these layers.

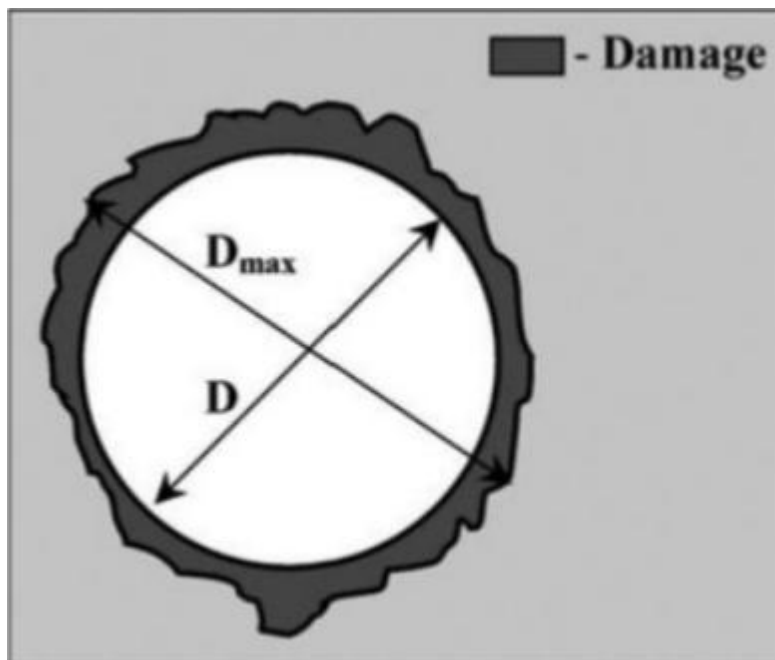


Figure 3.1 Diagrammatical calculation of delamination factor⁴

$$F_d = D_{max} / D_{nom}$$

In this equation, D_{max} and D_{nom} denote the maximum diameter of the observed defect and the hole nominal diameter, respectively.

Delamination factor at hole entry is termed as entry delamination factor whereas delamination factor at the hole end is known as exit delamination factor.



Figure 3.2 Leica microscope(Thapar university, Patiala)

3.2.2 Surface roughness

Surface roughness was measured by movement of stylus over the hole surface and amplifying the vertical and horizontal movement of stylus to produce a trace using mitutoyo surface roughness tester.



Figure 3.3 Mitutoyo surface roughness tester(Thapar University, Patiala)

3.2.3 Diameter deviation

Diametrical deviation of hole was calculated in this response using profile projector. Diameter value obtained was compared with the tool diameter(8mm).

3.3 Selection of Orthogonal array

The experiments were planned based on the design of experiments using Taguchi's orthogonal approach. The orthogonal array is used to study the entire parameter space with less number of experiments.

L₁₈ orthogonal array was used to perform the experiments. It is a mixed level orthogonal array in which one factor is at two level and the remaining three factors are at three levels each. It allows for the estimation of interaction effects along with main effects. One replication for each of experiments were performed.

Table 3.1 Experiment design Orthogonal array L₁₈

Exp no.	Coolant	Tool	Speed (RPM)	Feed (mm/min)
1	On	Twist drill	800	10
2	On	Twist drill	1000	15
3	On	Twist drill	1200	20
4	On	Brad point	800	10
5	On	Brad point	1000	15
6	On	Brad point	1200	20
7	On	End mill	800	15
8	On	End mill	1000	20
9	On	End mill	1200	10
10	Off	Twist drill	800	20
11	Off	Twist drill	1000	10
12	Off	Twist drill	1200	15
13	Off	Brad point	800	15
14	Off	Brad point	1000	20

15	Off	Brad point	1200	10
16	Off	End mill	800	20
17	Off	End mill	1000	10
18	Off	End mill	1200	15

3.4 Work Material

The material used was CFRP composite material with characteristics: Warp Fiber- Carbon Fiber 3K 200 tex, Weft Fiber- Carbon Fiber 3K 200 tex. Weight Distribution 50% warp : 50% weft with an orientation of 0/90°. The work piece material used was in the form of a 150mmX100mmX2 mm sheet.

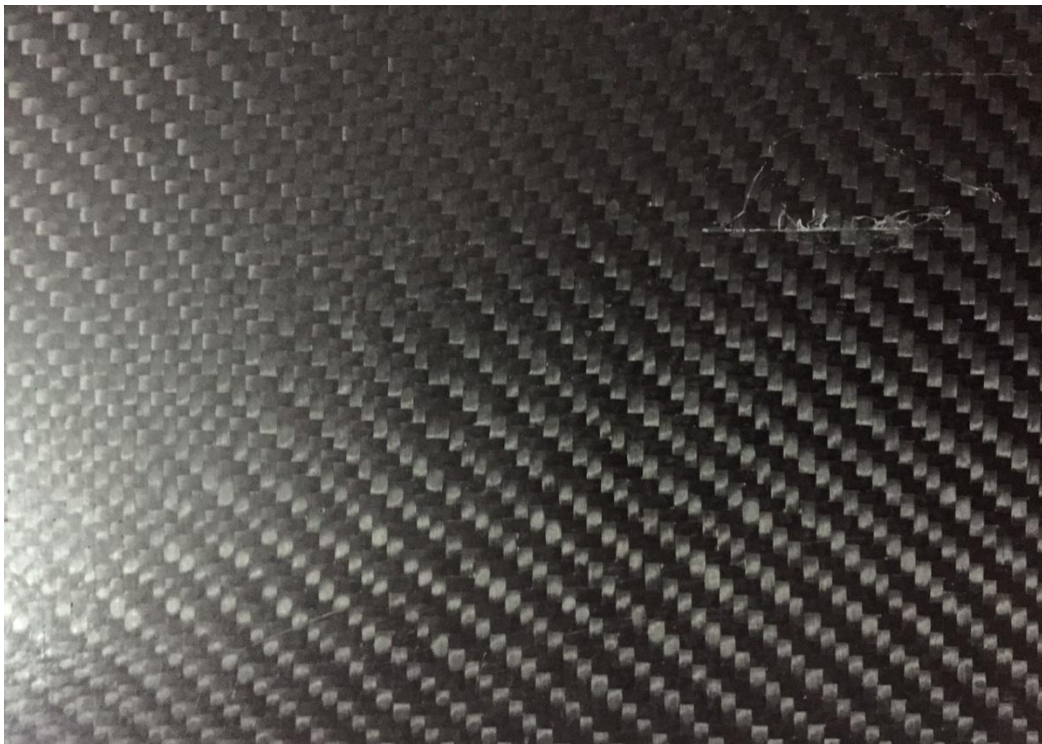


Figure 3.4 CFRP sheet used as workpiece in experiment

3.5 Tool Material

Tools used for drilling were 8 mm in diameter and material for all is HSS(high speed steel).



Figure 3.5 HSS twist drill(8mm diameter)



Figure 3.6 HSS brad point drill(8mm diameter)



Figure 3.7 Six Flute HSS end mill(8mm diameter)

3.6 Experimental setup

A computer numerical control (CNC) vertical machining center was used to set the prefixed drilling conditions, viz. the speed at which the spindle rotates and the rate at which the drill advances (feed rate). Experiments were performed on FANUC CNC vertical machining centre at Thapar university, patiala. The highest power input to the machine is 22400 W. The highest revolutions per minute are 8100 rpm, its coolant capacity is 208 Litres. The maximum length and width of machine is 1219 mm and 457 mm. The maximum tool diameter that can be held in tool holder is 89 mm. It is a three axis machine which follows instructions in form of G codes and M codes.



Figure 3.8 FANUC CNC machining centre(Thapar University, Patiala)

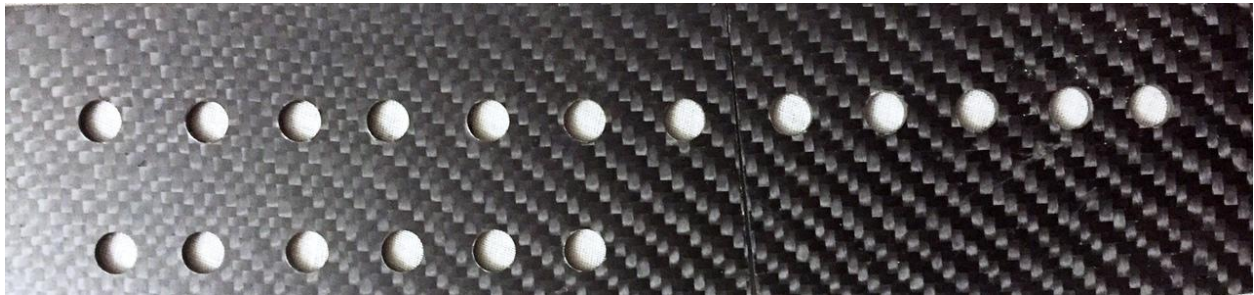


Figure 3.9 CFRP workpiece after experiment on FANUC CNC machining centre.

Chapter 4

Results and analysis

4.1 Introduction

The effect of input parameters i.e. speed, coolant, feed and tool type and their interactions were observed on the output parameters viz entry delamination factor, exit delamination factor, diametrical deviation and surface roughness using ANOVA(Analysis of Variance) method. A confidence level of 95% was used during the calculations.

4.2 Entry Delamination factor

Entry delamination factor was calculated using the relation

$$F_d = D_{\max} / D_{\text{nom}}$$

where D_{\max} and D_{nom} denote the maximum diameter of the observed defect and the hole nominal diameter at entry, respectively. D_{\max} and D_{nom} were calculated by measuring the damaged area using Leica microscope as illustrated in figure 4.1.

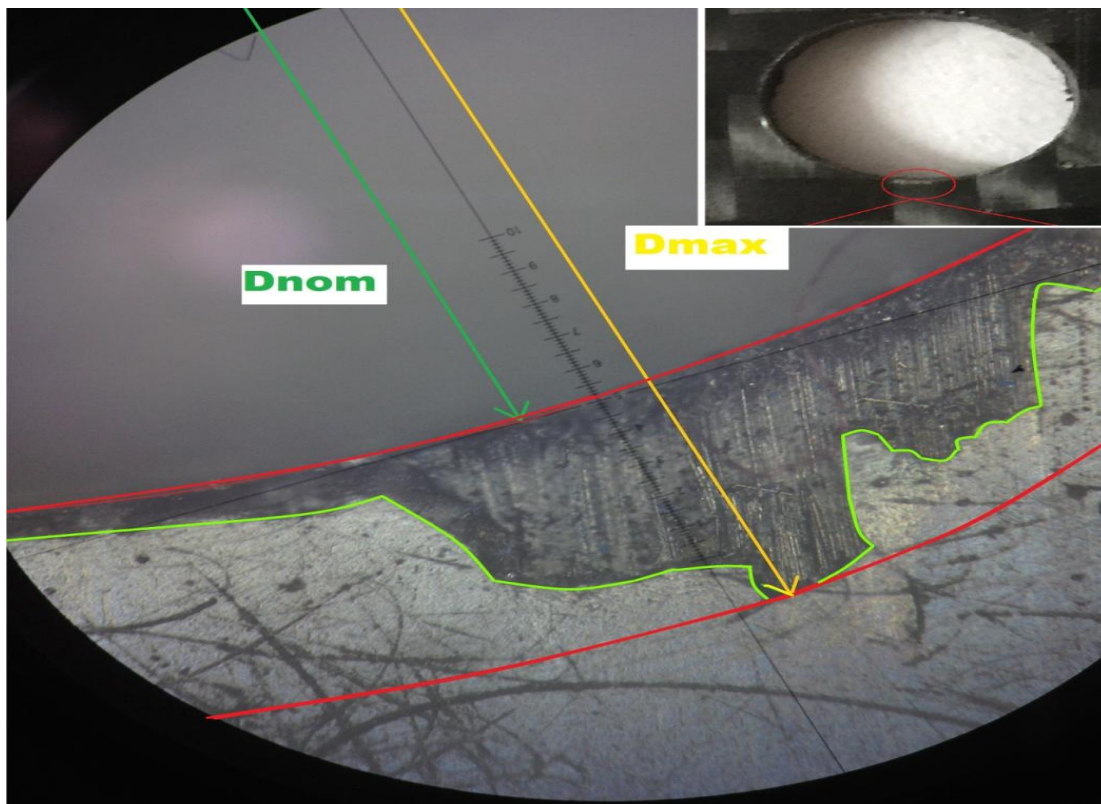


Figure 4.1 Damaged area calculation using Leica microscope

Table 4.1 illustrates the values of entry delamination factor calculated for various experiments performed and S/N ratio.

Table 4.1 Results for entry delamination factor

Exp no.	Coolant	Tool	Speed (RPM)	Feed (mm/min)	Entry Delamination Factor (F_d)		Mean	S/N Ratio(dB)
1	On	Twist drill	800	10	1.0458	1.0918	1.0688	-0.5793
2	On	Twist drill	1000	15	1.0920	1.1320	1.1120	-0.9235
3	On	Twist drill	1200	20	1.1340	1.1700	1.1520	-1.23011
4	On	Brad point	800	10	1.0210	1.0742	1.0476	-0.4067
5	On	Brad point	1000	15	1.0329	1.0834	1.0579	-0.04934
6	On	Brad point	1200	20	1.0416	1.0916	1.0666	-0.5624
7	On	End mill	800	15	1.0770	1.1090	1.0930	-0.7733
8	On	End mill	1000	20	1.1640	1.1900	1.1770	-1.4160
9	On	End mill	1200	10	1.2240	1.2460	1.2350	-1.8336
10	Off	Twist drill	800	20	1.0236	1.0696	1.0466	-0.3977
11	Off	Twist drill	1000	10	1.0961	1.1361	1.1161	-0.9554
12	Off	Twist drill	1200	15	1.1454	1.1814	1.1634	-1.3156

13	Off	Brad point	800	15	1.0337	1.0867	1.0602	-0.5104
14	Off	Brad point	1000	20	1.0531	1.1041	1.0786	-0.6594
15	Off	Brad point	1200	10	1.0670	1.1170	1.0920	-0.7667
16	Off	End mill	800	20	1.0223	1.0543	1.0383	-0.3274
17	Off	End mill	1000	10	1.1455	1.1715	1.1585	-1.2784
18	Off	End mill	1200	15	1.2446	1.2666	1.2556	-1.9773

Analysis of variance- Entry delamination factor

The results for entry delamination factor were analyzed using ANOVA for identifying the significant factors affecting the output parameters. Analysis of Variance for entry delamination factor was calculated using MINITAB software and the results of ANOVA are presented in table 4.2. The p value was observed to find significance of each factor and their interaction. The principal of the p value is that the value less than 0.05 then that factors or interactions are significant if value is more than 0.05 then that factors or interactions are insignificant.

Table 4.2 ANOVA for means for entry delamination factor

Source	DOF	Seq SS	Adj MS	F	P	% contribution	Status
Coolant	1	0.000	0.000	0.00	0.994	0	Insignificant
Tool	2	0.0256	0.0128	39.98	0.002	45.19	Significant
Speed	2	0.0312	0.0083	26.04	0.005	29.43	Significant
Feed	2	0.0032	0.0016	5.13	0.079	5.79	Insignificant
Coolant*feed	2	0.0068	0.0047	14.66	0.014	16.56	Significant
Tool*feed	4	0.0034	0.0008	2.65	0.184	2.99	Insignificant
Error	4	0.0012	0.00032				

Total	17	0.0716					
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S = 0.0179180 R-Sq = 98.21% R-Sq(adj) = 92.38%

Table 4.2 shows that factor tool type has p value 0.002 which is less than 0.05 and factor spindle speed has p value 0.005 which concludes that both of these factors have significant effect (p value < 0.05) on the entry delamination factor. Interaction of coolant and feed (p value 0.014) has a significant effect on output factor. All other factors and interactions have insignificant effect on the output parameter under consideration. The percentage contribution tool type is about 45.19% whereas for spindle speed the percentage contribution is about 29.43%. Percentage contribution of coolant and feed interaction was found out to be 16.56%.

Table 4.3 Response table for means for entry delamination factor

Level	Coolant	Tool	Speed	Feed
1	1.112	1.110	1.070	1.120
2	1.112	1.084	1.117	1.124
3		1.183	1.165	1.093
Delta	0.000	0.099	0.095	0.031
Rank	4	1	2	3

Table 4.3 shows the ranks of various factors in terms of their relative significance. The table shows that tool type has been assigned the first rank followed by spindle speed, feed and coolant. Coolant therefore has negligible effect on the entry delamination factor.

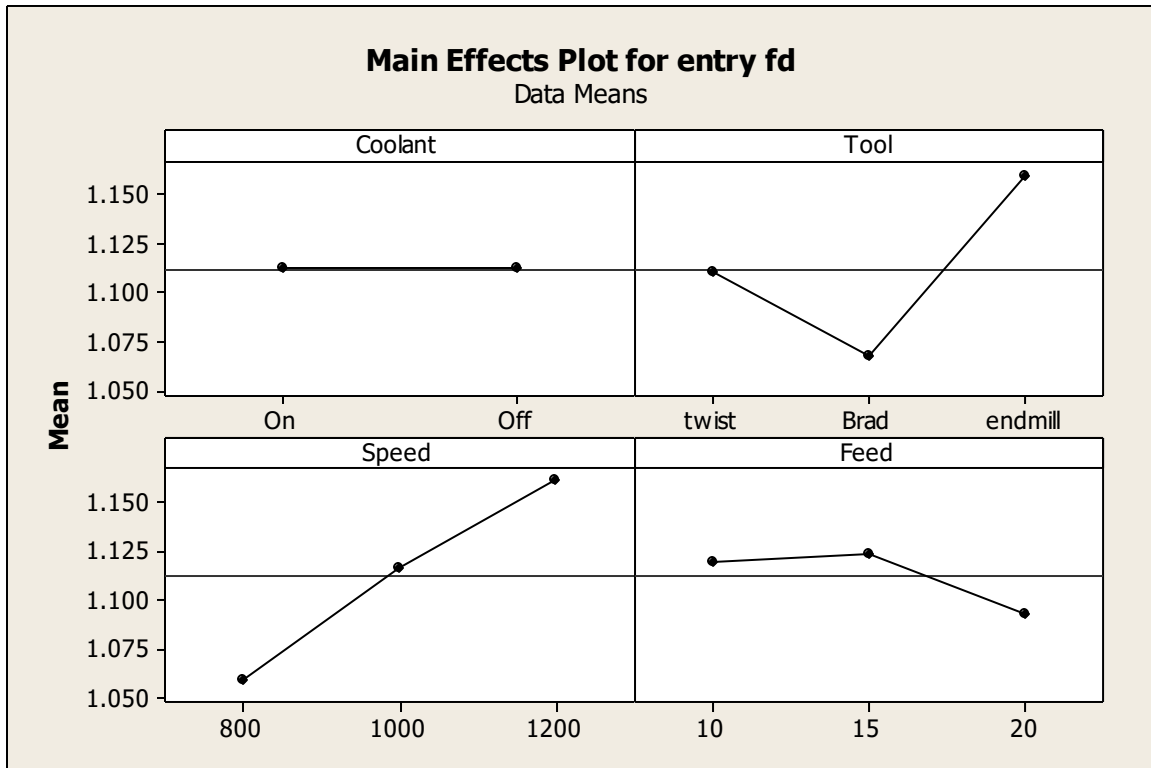


Figure 4.2 Main effect plots of means for entry delamination factor

It has been observed that coolant has no effect on the entry delamination factor whereas according to plot between tool and entry Fd, brad point drill has minimum delamination factor which concludes that minimum entry delamination takes place during drilling with brad point drill. On the other hand maximum entry delamination takes place while drilling with end mill. It is also observed that as the spindle speed increases the entry delamination goes on increasing with maximum at 1200 rpm. Feed has relatively little effect on entry delamination with maximum entry delamination at 15 mm/min and minimum at 20 mm/min.

Figure 4.3 shows the interaction plots of input factors i.e. the combined effect of two factors on the output. According to ANOVA interaction between coolant and feed has a significant effect on the entry delamination factor while other interactions are insignificant.

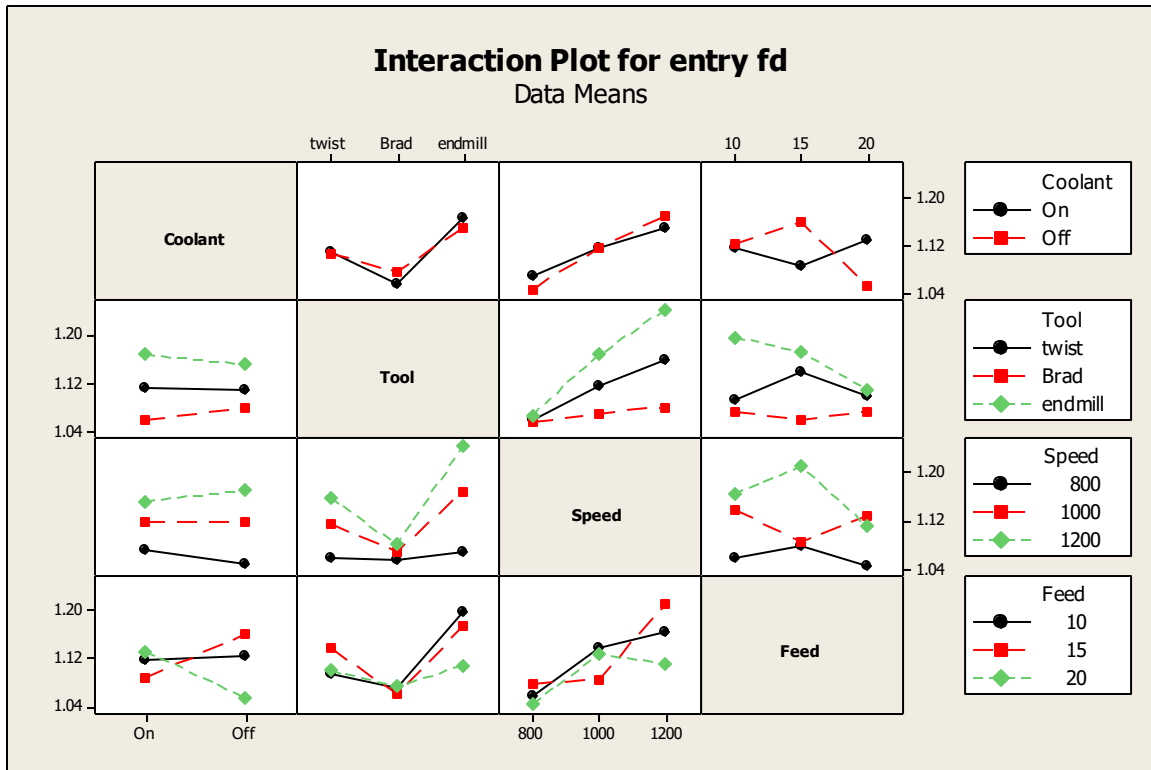


Figure 4.3 Interaction plot for means entry delamination factor

Results for S/N Ratio of Entry Delamination Factor

S/N ratio known as signal to noise ratio is an indication of amount of variation present in the process. The control factors that contribute to reduced variation are identified by viewing at the amount of variation present as a response.

The S/N ratio, which combines multiple values within a trial, depends on type of characteristic being evaluated. The three different response characteristics are given by: Higher the better, Lower the better, Nominal the best.

Entry delamination factor is lower the best characteristic which is given by:

$$S/N_{LB} = -10 \log \left[\frac{\sum_1^r y^2}{r} \right]$$

where:

y is observed value of entry delamination factor for a given experiment

r is the number of repetitions performed for a given experiment

Table 4.4 shows ANOVA calculation for S/N ratio. It has been seen that factor tool type has p value 0.003 which is less than 0.05 and factor spindle speed has p value 0.006 which concludes

that both of these factors have significant effect(p value <0.05) on S/N ratio. Interaction of coolant and feed(p value 0.018) has a significant effect. All other factors and interactions have insignificant effect on signal to noise ratio. The percentage contribution tool type is about 46.03% whereas for spindle speed the percentage contribution is about 30.01%. Percentage contribution of coolant and feed interaction was found out to be 16.12%.

Table 4.4 ANOVA table for S/N ratio for entry delamination factor

Source	DOF	Seq SS	Adj MS	F	P	% contribution	Status
Coolant	1	0.000	0.000	0.00	0.962	0	Insignificant
Tool	2	1.476	0.738	36.64	0.003	46.03	Significant
Speed	2	1.849	0.480	23.85	0.006	30.01	Significant
Feed	2	0.194	0.097	4.82	0.086	6.11	Insignificant
Coolant*feed	2	0.380	0.264	13.11	0.018	16.12	Significant
Tool*feed	4	0.192	0.048	2.38	0.210	1.73	Insignificant
Error	4	0.080	0.020				
Total	17						

$$S = 0.141930 \quad R\text{-Sq} = 98.07\% \quad R\text{-Sq}(\text{adj}) = 91.79\%$$

Table 4.5 shows the ranks of various factors in terms of their variation in their S/N ratio. The table shows that tool type has been assigned the first rank followed by spindle speed, feed and coolant.

Table 4.5 Response table for S/N ratio for entry delamination factor

Level	Coolant	Tool	Speed	Feed
1	-0.9132	-0.905	-0.499	-0.970
2	-0.9099	-0.496	-0.954	-0.998
3		-1.3177	-1.281	-0.765
Delta	0.0034	0.8212	0.7817	0.233
Rank	4	1	2	3

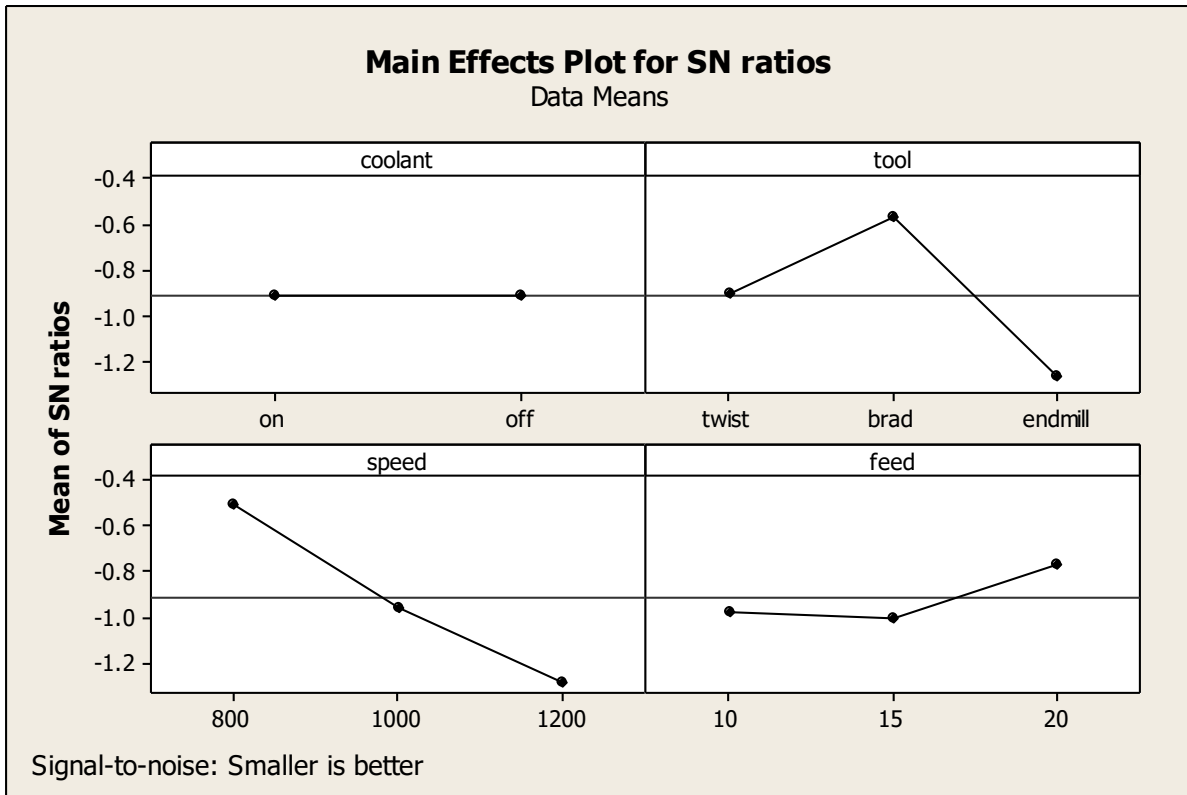


Figure 4.4 Main effect plots of S/N ratio for entry delamination factor

Figure 4.4 shows that coolant has no effect on S/N ratio whereas tool type has prominent effect. As shown in graph brad point drill has highest value of S/N ratio which shows that it has least variation in the observed data points whereas end mill has large variation in the process. On other hand at 800 rpm highest S/N ratio is seen while minimum S/N occurs at 1200 rpm thereby depicting a linear behaviour. Tool feed at 20 mm/min has maximum S/N ratio giving least variation in process as compared to other levels of tool feed.

Figure 4.5 shows the interaction plots of input factors i.e. the combined effect of two factors on signal to noise ratio. According to ANOVA interaction between coolant and feed has a significant effect on S/N ratio

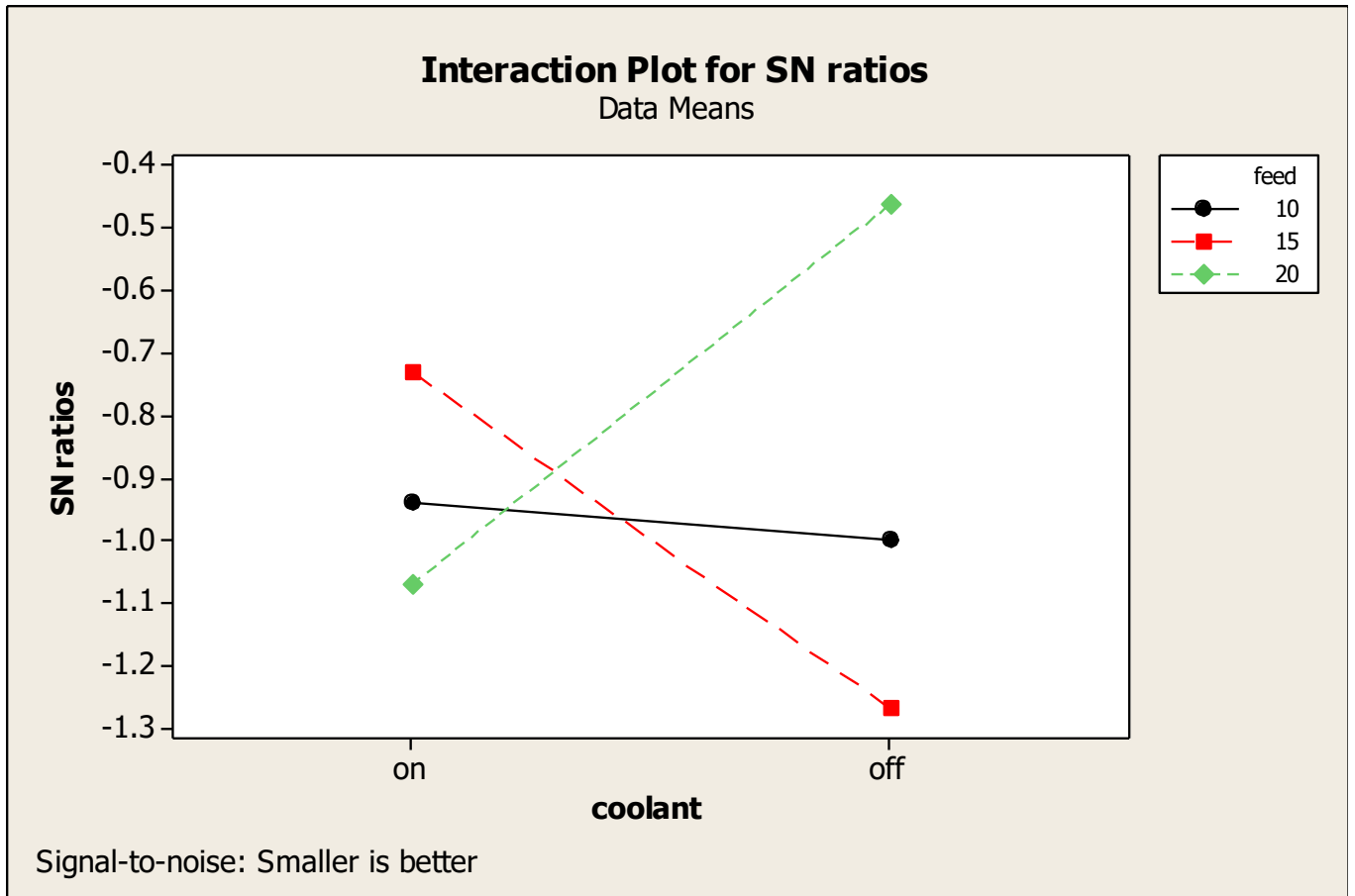


Figure 4.5 Interaction plot(coolant and feed) of S/N ratio for entry delamination factor

Estimating the mean

Mean value of entry delamination factor is given by

$$\mu = \text{tool}_2 + \text{speed}_1 + \text{coolant}_2 \text{feed}_3 - 2T$$

Where T is given as mean entry delamination factor /no. of experiments.

$$\mu = 1.08415 + 1.07008 + 1.1237 - 2 * 1.1121$$

$$\mu = 1.05373$$

Confidence Interval around the Estimated Mean

Confidence Interval around the estimated tensile strength mean

$$C.I. = \sqrt{(F_{v1,v2} \times \frac{Ve}{\eta_{eff}})}$$

Where $F \propto v1v2 = F$ ratio

$\alpha = \text{risk (0.05)}$

confidence = 1- α

$v_1 = \text{dof for mean which is always =1}$

$v_2 = \text{dof for error } V_e = \text{Variance for error}$

$\eta_{\text{eff}} = \text{number of test under that condition using the participating factors}$

$\eta_{\text{eff}} = N / (1 + \text{dof tool, speed, coolant*feed}) = 18 / (1 + 2 + 2 + 2) = 2.57$

$$C.I. = \sqrt{4.67 \times \frac{0.0003}{2.57}}$$

C.I. = 0.02334

So the confidence interval level around the entry delamination factor is given by 1.05373±0.02334.

4.3 Exit Delamination factor

The corresponding diameter(D_{max}) were noted down at exit of hole. The results for exit delamination factor for all the experiments performed have been measured using leica microscope and their S/N ratio are compiled in table 4.6.

Table 4.6 Results for exit delamination factor and S/N ratio

Exp no.	Coolant	Tool	Speed (RPM)	Feed (mm/min)	Exit Delamination Factor (F_d)		Mean	S/N Ratio(dB)
1	On	Twist drill	800	10	1.1388	1.2088	1.1738	-1.3957
2	On	Twist drill	1000	15	1.3913	1.4533	1.4223	-3.0618
3	On	Twist drill	1200	20	1.1117	1.1657	1.1387	-1.1306
4	On	Brad point	800	10	1.1371	1.1831	1.1601	-1.2916
5	On	Brad point	1000	15	1.1281	1.1661	1.1471	-1.1932
6	On	Brad point	1200	20	1.6580	1.6900	1.6740	-4.4755
7	On	End mill	800	15	1.4830	1.5070	1.4950	-3.4931
8	On	End mill	1000	20	1.4569	1.4769	1.4669	-3.3282
9	On	End mill	1200	10	1.3670	1.3830	1.3750	-2.7662
10	Off	Twist drill	800	20	1.1978	1.1318	1.1648	-1.3285

11	Off	Twist drill	1000	10	1.5079	1.4499	1.4789	-3.4004
12	Off	Twist drill	1200	15	1.3359	1.2859	1.3109	-2.3529
13	Off	Brad point	800	15	1.4412	1.3992	1.4202	-3.0479
14	Off	Brad point	1000	20	1.5420	1.5080	1.5250	-3.6659
15	Off	Brad point	1200	10	1.5118	1.4838	1.4978	-3.5094
16	Off	End mill	800	20	1.5579	1.5379	1.5479	-3.7950
17	Off	End mill	1000	10	1.6392	1.6232	1.6312	-4.2502
18	Off	End mill	1200	15	1.6913	1.6793	1.6853	-4.5336

Analysis of variance- Exit delamination factor

The results for exit delamination factor were analyzed using ANOVA for identifying the significant factors affecting the output parameters. Analysis of Variance for exit delamination factor was calculated using MINITAB software and the results of ANOVA are presented in table 4.7. The p value was observed to find significance of each factor and their interaction.

Table 4.7 ANOVA table for means for exit delamination factor

Source	DOF	Seq SS	Adj MS	F	P	% Contribution	Status
Coolant	1	0.0812	0.0812	18.56	0.049	28.58	Significant
Tool	2	0.1905	0.0952	21.77	0.044	33.68	Significant
Speed	2	0.0567	0.0029	0.68	0.596	1.04	Insignificant
Feed	2	0.0038	0.0079	1.82	0.355	2.80	Insignificant
Coolant*feed	2	0.0280	0.0276	6.32	0.137	9.73	Insignificant
Coolant*speed	2	0.0243	0.0207	4.73	0.174	7.28	Insignificant
Tool*speed	4	0.1882	0.0471	10.75	0.087	16.55	Insignificant
Error	2	0.0087	0.0043				
Total	17	0.5817					

S = 0.0661563 R-Sq = 98.50% R-Sq(adj) = 87.21%

Table 4.7 shows the F values, P values and percent contribution of main factors and interactions. It has been observed that tool type and coolant both have p value 0.044 and 0.049 respectively

thereby concluding that both of these factors are having significant effect ($p \text{ value} < 0.05$) on the exit delamination factor. Percentage contribution of tool type on output is 33.68% whereas for coolant the percent contribution is nearly 28.58% followed by interaction between tool and speed accounting for 16.55%. Other factors have very low contribution and are thus assumed to be insignificant.

Table 4.8 Response table for exit delamination factor

Level	Coolant	Tool	Speed	Feed
1	1.339	1.282	1.327	1.386
2	1.474	1.404	1.445	1.413
3		1.534	1.447	1.420
Delta	0.134	0.252	0.120	0.033
Rank	2	1	3	4

Table 4.8 shows that 1st rank has been assigned to tool type factor which has most significant effect on the exit delamination. 2nd rank has been given to coolant which is also having a significant effect on output followed by spindle speed and feed rate.

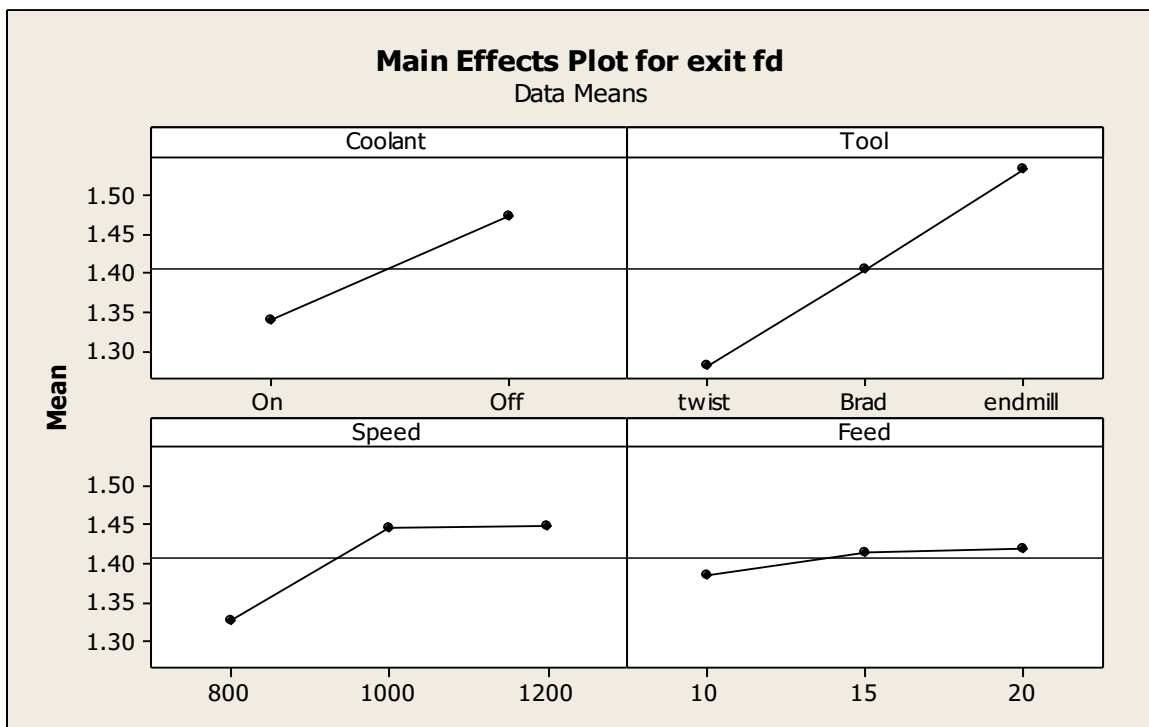


Figure 4.6 Main effect plots of means for exit delamination factor

Fig 4.6 depicts the main effect plots of four input factors viz spindle speed, feed, coolant and tool type. From the plot it is observed that when the coolant is turned off there is increased tendency of exit delamination. However on observing the plot of tool type it can be concluded that on drilling with twist drill there is low delamination as compared with that during drilling of CFRP using end mill which results in increased exit delamination. Plot of spindle speed vs exit delamination depicts that as the spindle speed increases the exit delamination goes on increasing with maximum delamination occurring at 1200 rpm. Effect of feed rate on exit delamination is considerably less with minimum delamination occurring at feed rate of 10mm/min and maximum at 20mm/min.

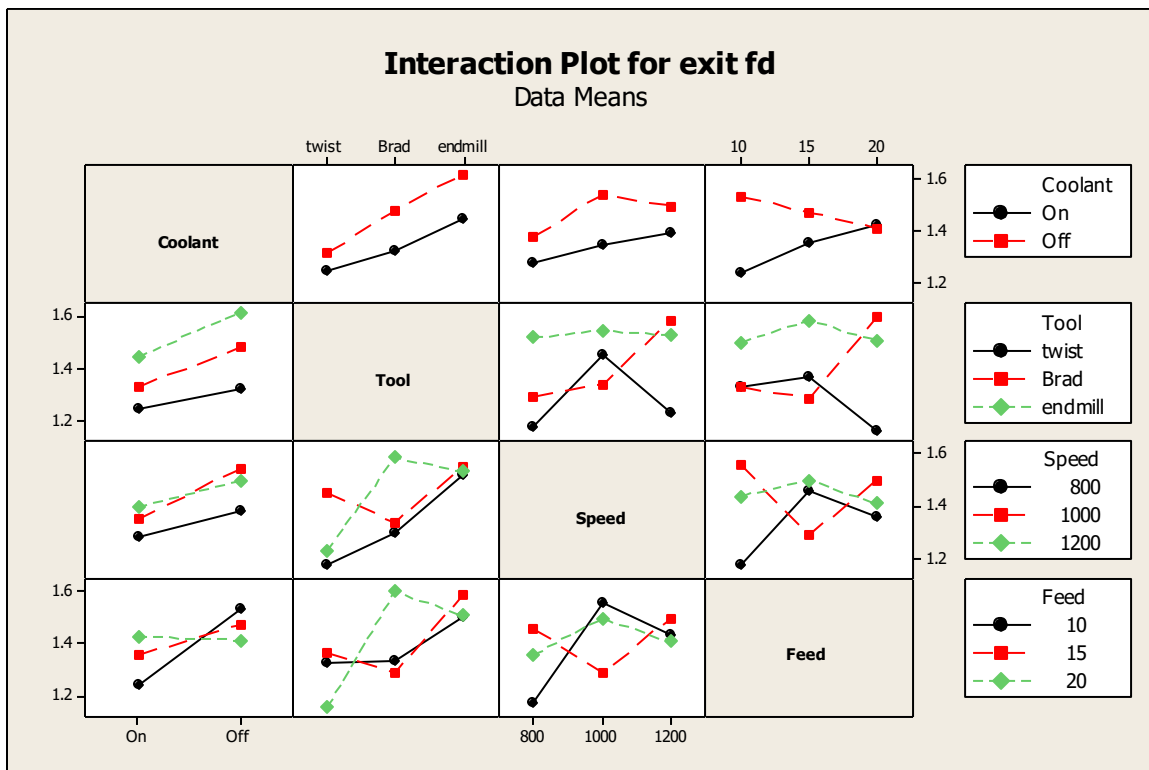


Figure 4.7 Interaction plot for means exit delamination factor

Fig 4.7 shows the interaction plots of various factors vs exit delamination factor. As calculated using ANOVA combined effect of tool type and feed rate has percent contribution of 16.55% but still this interaction has insignificant effect on exit delamination factor. Other interactions have no significant effect on the output factor.

Results for S/N Ratio of Exit Delamination Factor

Entry delamination factor is lower the best characteristic which is given by:

$$S/N_{LB} = -10 \log \left[\frac{\sum_1^r y^2}{r} \right]$$

where:

y is observed value of exit delamination factor for a given experiment

r is the number of repetitions performed for a given experiment

Table 4.9 ANOVA table for S/N ratio for exit delamination factor

Source	DOF	Seq SS	Adj MS	F	P	% Contribution	Status
Coolant	1	3.335	3.335	22.04	0.042	29.09	Significant
Tool	2	7.521	3.760	24.85	0.039	32.86	Significant
Speed	2	2.233	0.117	0.77	0.565	1.02	Insignificant
Feed	2	0.132	0.361	2.39	0.295	3.15	Insignificant
Coolant*speed	2	0.873	0.855	5.65	0.150	7.46	Insignificant
Coolant*feed	2	1.071	1.067	7.06	0.124	9.32	Insignificant
Tool*speed	4	7.776	1.944	12.85	0.074	16.96	Insignificant
Error	2	0.302	0.151				
Total	17	23.245					

$$S = 0.388994 \quad R\text{-Sq} = 98.70\% \quad R\text{-Sq}(\text{adj}) = 88.93\%$$

Table 4.9 shows the F values, P values and percent contribution of main factors and interactions. It has been observed that tool type and coolant both have p value 0.039 and 0.042 respectively thereby concluding that both of these factors are having significant effect (p value < 0.05) on the variation in the process. Percentage contribution of tool type on output is 32.86% whereas for coolant the percent contribution is nearly 29.09% followed by interaction between tool and speed accounting for 16.96%. Other factors have very low contribution and are thus assumed to be insignificant.

Table 4.10 Response table for S/N ratio for exit delamination factor

Level	Coolant	Tool	Speed	Feed
1	-2.460	-2.112	-2.392	-2.769
2	-3.320	-2.864	-3.150	-2.947
3		-3.694	-3.128	-2.954
Delta	0.861	1.583	0.758	0.185
Rank	2	1	3	4

Table 4.10 shows the ranks of various factors in terms of their variation in their S/N ratio. The table shows that tool type has been assigned the first rank followed by coolant. While spindle speed and feed rate has been assigned third and fourth rank respectively.

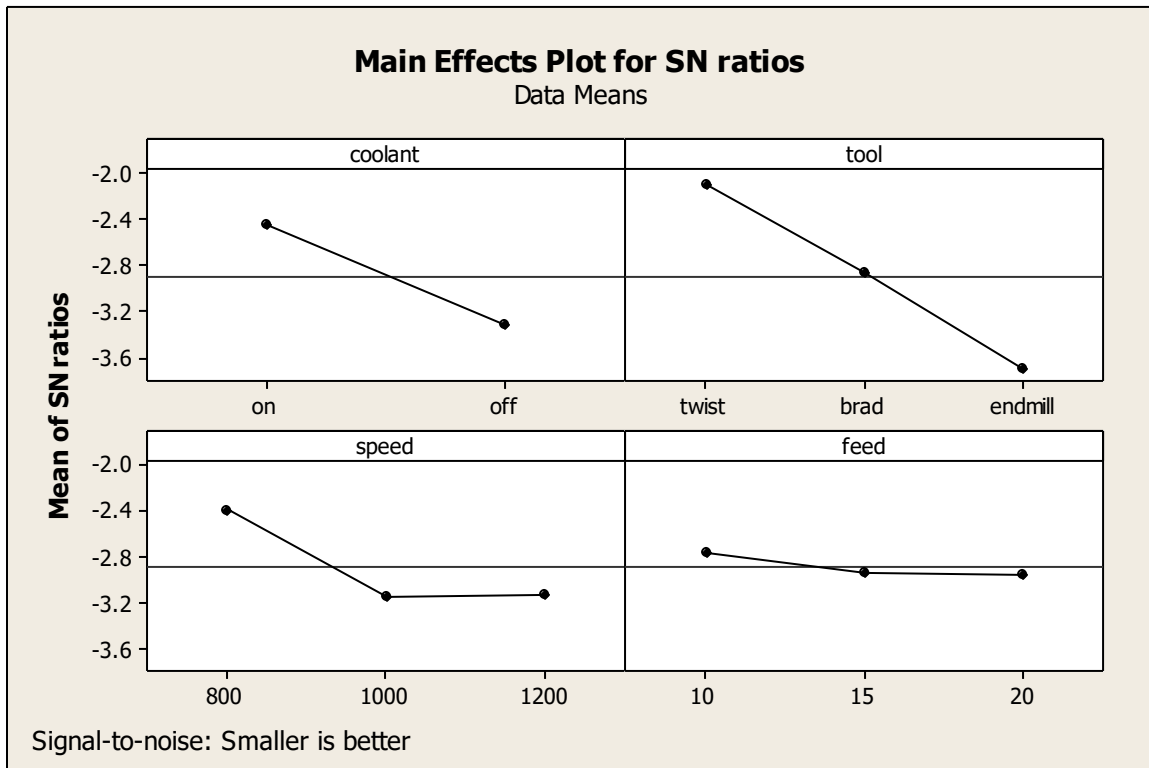


Figure 4.8 Main effect plots of S/N ratio for exit delamination factor

Figure 4.8 shows that when coolant is on it leads to low variation in the process as compared to when it is in off position. End mill tool has very low S/N ratio resulting in large variability while machining with twist drill leads to low variation in the process. Coolant and tool type possess linear variation in S/N ratio with different levels. Machining at 800 rpm leads to high S/N ratio thereby influencing the variation minimally. All levels of feed rate have nearly same effect on

variation. Figure 4.9 shows combined effect of tool type and spindle speed on S/N ratio which concludes that their combined effect has some effect(F value 12.85, p value 0.074) on S/N ratio but the effect is still insignificant. Other interactions have been observed to be totally insignificant.

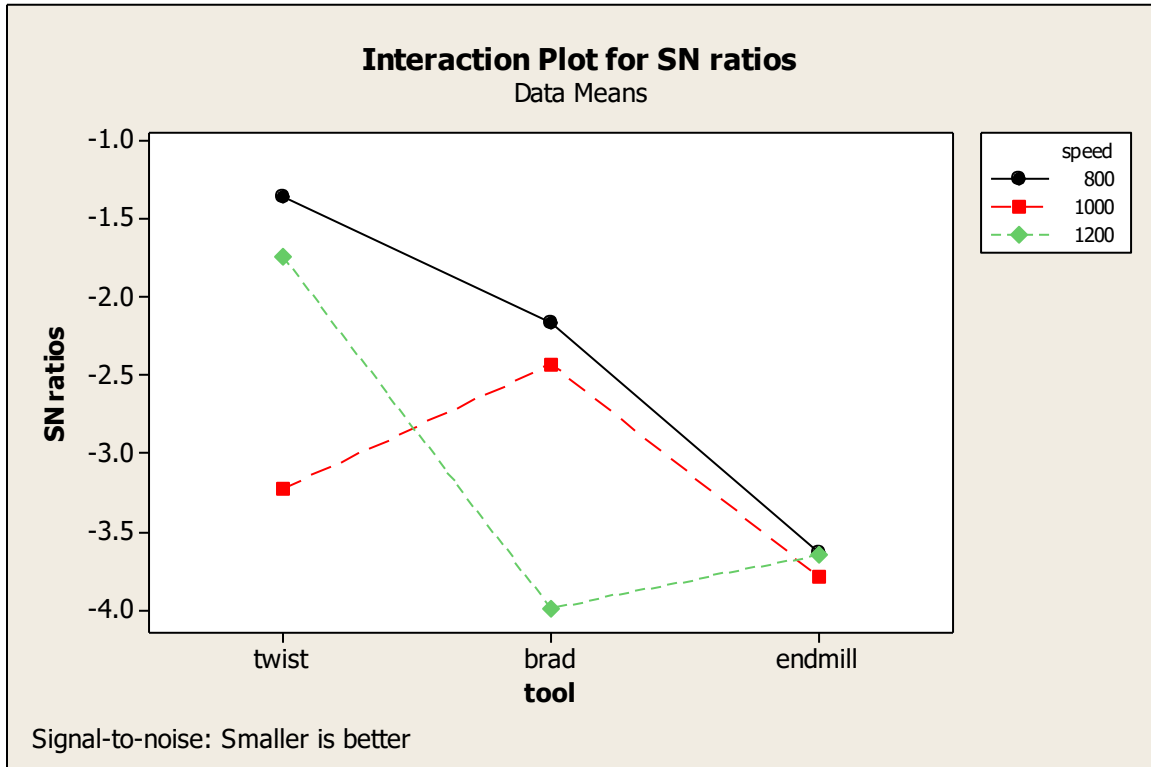


Figure 4.9 Interaction plot (tool and speed) of S/N ratio for exit delamination factor

Estimating the mean

Mean value of exit delamination factor is given by

$$\mu = \text{coolant}_1 + \text{tool}_1 - T$$

Where T is given as mean exit delamination factor /no. of experiments.

$$\mu = 1.339 + 1.282 - 1.375$$

$$\mu = 1.246$$

Confidence Interval around the Estimated Mean

Confidence Interval around the estimated exit delamination factor

$$C.I. = \sqrt{(F_{v_1, v_2} \times \frac{V_e}{\eta_{eff}})}$$

Where $F \propto v_1 v_2 = F$ ratio

$\alpha = \text{risk (0.05)}$

confidence = $1 - \alpha$

$v_1 = \text{dof for mean which is always } = 1$

$v_2 = \text{dof for error } \quad V_e = \text{Variance for error}$

$\eta_{\text{eff}} = \text{number of test under that condition using the participating factors}$

$\eta_{\text{eff}} = N / (1 + \text{dof tool, coolant}) = 18 / (1 + 1 + 2) = 4.5$

$$C.I. = \sqrt{4.60 \times \frac{0.0043}{4.5}}$$

C.I. = 0.0662

So the confidence interval level around the exit delamination factor is given by 1.246 ± 0.0662 .

4.4 Surface Roughness(R_a)

Results of surface roughness measured by Mitutoyo surface roughness tester are shown in table 4.11

Table 4.11 Results for Surface roughness and S/N ratios

Exp no.	Coolant	Tool	Speed (RPM)	Feed (mm/min)	Surface roughness R_a		Mean	S/N Ratio (dB)
					(μm)			
1	On	Twist drill	800	10	0.56	0.38	0.47	6.4017
2	On	Twist drill	1000	15	0.91	0.75	0.83	1.5783
3	On	Twist drill	1200	20	1.91	1.89	1.90	-5.575
4	On	Brad point	800	10	0.74	0.56	0.65	3.6592
5	On	Brad point	1000	15	0.35	0.19	0.27	5.0072
6	On	Brad point	1200	20	0.43	0.39	0.41	4.7340
7	On	End mill	800	15	0.61	0.41	0.51	5.6846
8	On	End mill	1000	20	1.24	1.12	1.18	-1.4488
9	On	End mill	1200	10	1.18	1.12	1.15	-1.2169
10	Off	Twist drill	800	20	0.44	0.60	0.52	5.5783
11	Off	Twist drill	1000	10	0.61	0.75	0.68	3.3040

12	Off	Twist drill	1200	15	1.47	1.57	1.52	-3.6415
13	Off	Brad point	800	15	0.45	0.65	0.55	5.0515
14	Off	Brad point	1000	20	1.02	1.14	1.08	-0.6819
15	Off	Brad point	1200	10	1.56	1.62	1.59	-4.0294
16	Off	End mill	800	20	1.01	1.17	1.09	-0.7718
17	Off	End mill	1000	10	0.52	0.66	0.59	4.5222
18	Off	End mill	1200	15	0.50	0.60	0.55	3.1570

Analysis of Variance- Surface Roughness

Results shown in table 4.11 were analysed using ANOVA to determine the factors which affect the surface roughness significantly. ANOVA for surface roughness was performed on MINITAB and results are shown in table 4.12. Factors having p value less than 0.05 are termed as significant factors.

Table 4.12 ANOVA table of means for surface roughness

Source	DOF	Seq SS	Adj MS	F	P	% Contribution	Status
Coolant	1	0.0355	0.0355	1.57	0.337	1.51	Insignificant
Tool	2	0.1594	0.0797	3.51	0.222	4.14	Insignificant
Speed	2	1.2997	0.5398	22.02	0.043	26.03	Significant
Feed	2	0.4175	0.4381	19.30	0.049	22.77	Significant
Coolant*tool	2	0.4602	0.3301	14.54	0.064	17.15	Insignificant
Coolant*speed	2	0.1486	0.2229	9.82	0.092	11.58	Insignificant
Tool*speed	4	1.0545	0.3136	13.81	0.069	16.29	Insignificant
Error	2	0.0454	0.0227				
Total	17	3.6210					

S = 0.150676 R-Sq = 98.75% R-Sq(adj) = 89.34%

Table 4.12 shows that spindle speed(p value 0.043) and feed rate(p value 0.049) are the factors significantly affecting the surface roughness of the drilled hole. Spindle speed has the maximum percentage contribution 26.03% which is followed by feed rate which has 22.77% contribution

and interaction of coolant and tool collectively accounts for 17.15%. Interaction of tool and speed contributes 16.29% whereas interaction of coolant and speed has 11.58% contribution.

Table 4.13 Response table for means for surface roughness

Level	Coolant	Tool	Speed	Feed
1	0.8189	0.9867	0.6317	0.8550
2	0.9078	0.7583	0.7717	0.7050
3		0.8450	1.1867	1.0300
Delta	0.0889	0.2283	0.5550	0.3250
Rank	4	3	1	2

Table 4.13 shows the ranks of main factors in terms of their relative significance. Table shows that 1st rank has been assigned to spindle speed as it has largest effect on surface roughness whereas 2nd rank is occupied by feed rate which is followed by tool type and coolant which occupies the last rank proving its least impact on the surface roughness.

Fig 4.10 shows the effect of main factors on the surface roughness of the hole. From the plot it has been

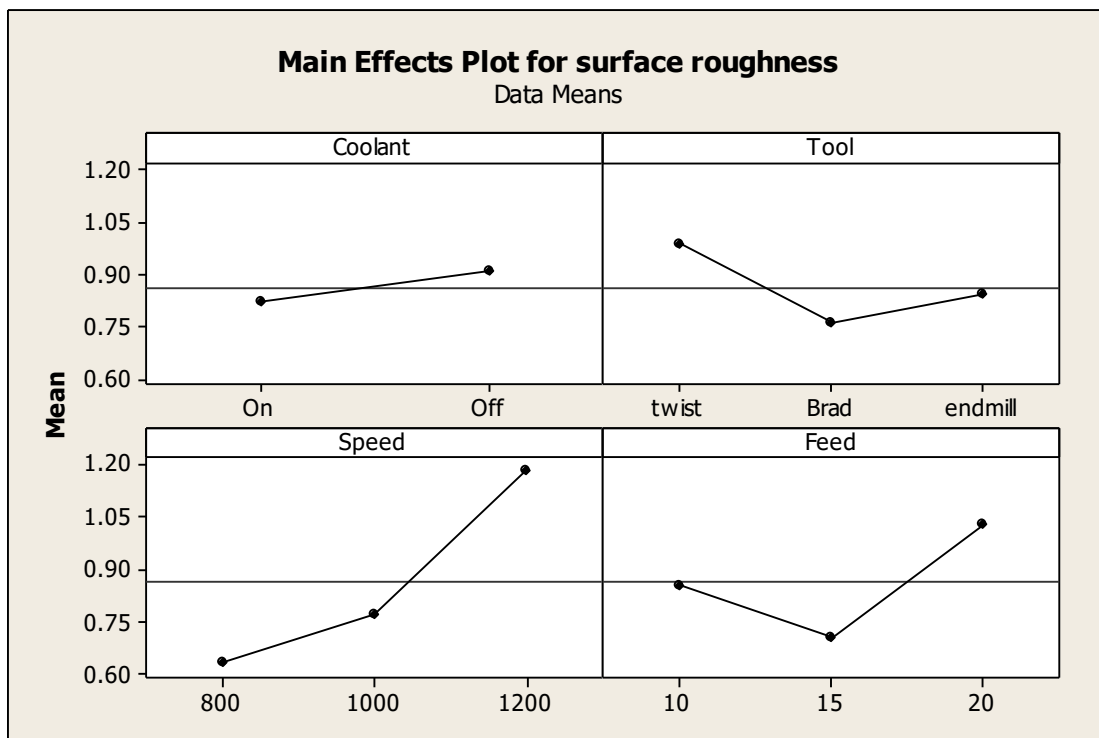


Figure 4.10 Main effects plot of means for surface roughness.

observed that hole surface quality improves when machining is performed with coolant turned on as compared to high surface roughness observed while drilling without coolant being turned on. Drilling performed using brad point drill results in very low surface roughness thereby providing excellent surface quality while drilling performed using twist drill leads to a very high surface roughness followed by machining using end mill. Spindle speed is seen to have an increasing trend in surface roughness with increase in spindle speed from 800rpm to 1200 rpm. With increase in feed rate from 10mm/min to 20mm/min surface roughness tends to decrease till it achieves a minimum value at 15mm/min. On further increasing the feed rate surface roughness again starts to increase to a maximum.

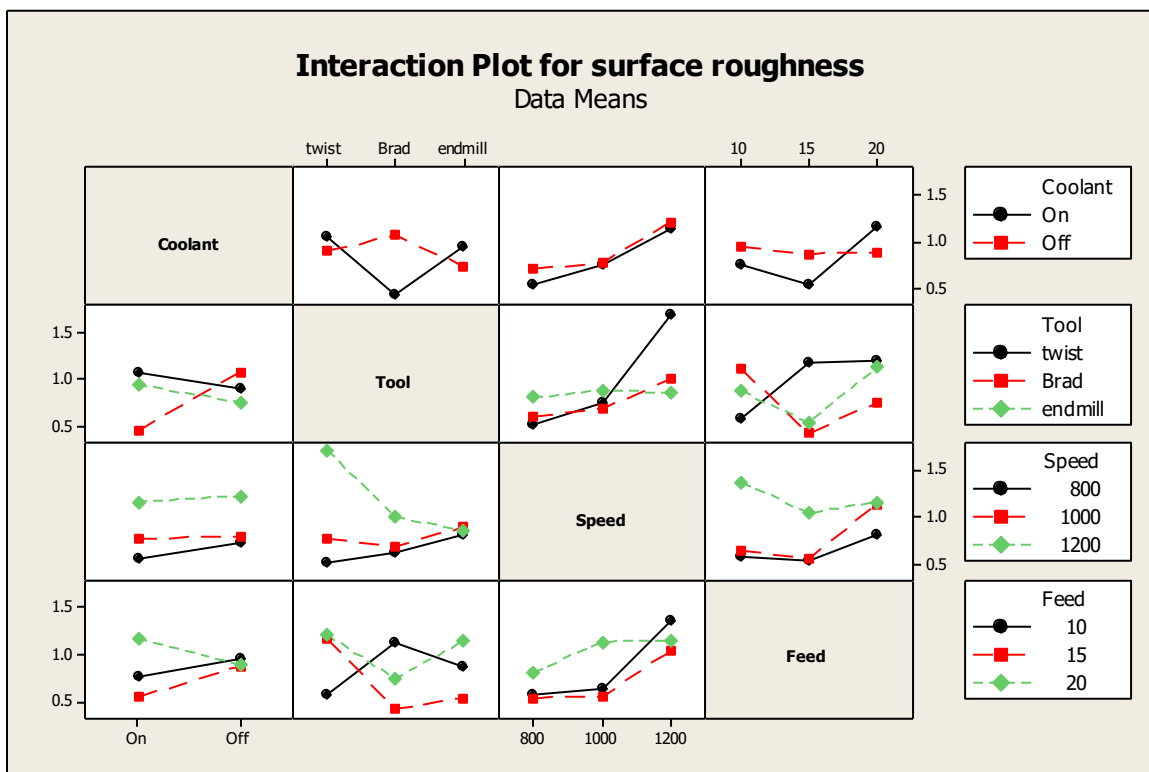


Figure 4.11 Interaction effects plots of means for surface roughness

Figure 4.11 depicts the interaction plots of various factors with surface roughness. It has been observed from ANOVA that no interaction has a significant effect on the surface roughness but interaction of coolant and tool has largest contribution of 17.15%. Interaction of tool and speed contributes 16.29% whereas interaction of coolant and speed has 11.58% contribution.

Results for S/N Ratio of Surface Roughness

The S/N ratios have been calculated to identify the major contributing factors and interactions that cause variation in the surface roughness.

Surface roughness is lower the best characteristic which is given by:

$$S/N_{LB} = -10 \log \left[\frac{\sum_1^r y^2}{r} \right]$$

where:

y is observed value of entry delamination factor for a given experiment

r is the number of repetitions performed for a given experiment

Table 4.14 ANOVA table for S/N ratio for surface roughness

Source	DOF	Seq SS	Adj MS	F	P	% contribution	Status
Coolant	1	2.230	2.230	1.43	0.354	1.61	Insignificant
Tool	2	3.161	1.581	1.02	0.496	1.14	Insignificant
Speed	2	87.123	43.562	27.98	0.035	31.35	Significant
Feed	2	19.970	33.429	21.48	0.044	24.05	Significant
Coolant*tool	2	30.059	15.030	9.66	0.094	10.81	Insignificant
Coolant*speed	2	14.763	21.844	14.03	0.067	15.71	Insignificant
Tool*speed	4	84.962	21.240	13.64	0.069	15.27	Insignificant
Error	2	3.113	1.557				
Total	17	245.38					

$$S = 1.24766 \quad R\text{-Sq} = 98.73\% \quad R\text{-Sq}(\text{adj}) = 89.22\%$$

Table 4.14 shows that spindle speed(p value 0.035) and feed rate(p value 0.044) are the factors significantly affecting the variation in surface roughness. Spindle speed has the maximum percentage contribution 31.35% followed by feed rate which has 24.05% contribution and interaction of coolant and tool collectively accounts for 10.81%. Interaction of tool and speed contributes 15.27% whereas interaction of coolant and speed has 15.71% contribution. Table 4.15 ranks main factors on basis of their variation in S/N ratio. Speed has been assigned first rank followed by feed, tool and feed rate in the same order.

Table 4.15 Response table for S/N ratio for surface roughness.

Level	Coolant	Tool	Speed	Feed
1	2.0916	1.2743	4.2673	2.1068
2	1.3876	2.2901	2.0469	2.8062
3		1.6544	-1.0954	0.3058
Delta	0.704	1.0159	5.3626	2.5004
Rank	4	3	1	2

Figure 4.12 shows effect of main factors on S/N ratio. It has been seen that coolant has linear graph with S/N ratio with maximum S/N ratio occurring when coolant is turned on. High S/N ratio has been observed when brad point drill is used leading to low variation. Drilling with spindle speed of 800 rpm gives high S/N ratio while worst is observed while operating at 1200 rpm. Feed rate of 15mm/min leads to a high S/N ratio thereby decreasing variation in the process as compared to feed rate of 20mm/min which has a low S/N ratio. Feed rate of 15 mm/min has intermediate value of S/N ratio in between 10 mm/min and 20 mm/min.

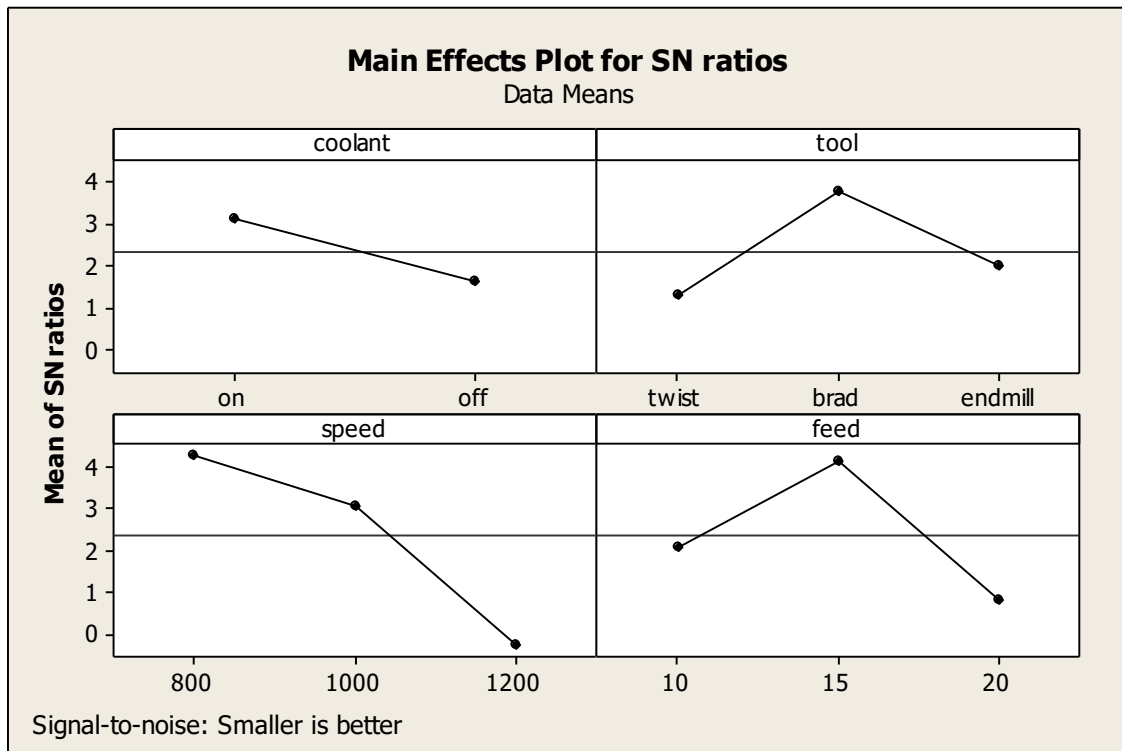


Figure 4.12 Main effect plots of S/N ratio for surface roughness

Figure 4.13 shows the relationship between interaction of coolant and speed with S/N ratio which has a high percent contribution 15.71% as shown in table 4.14 though its effect is insignificant.

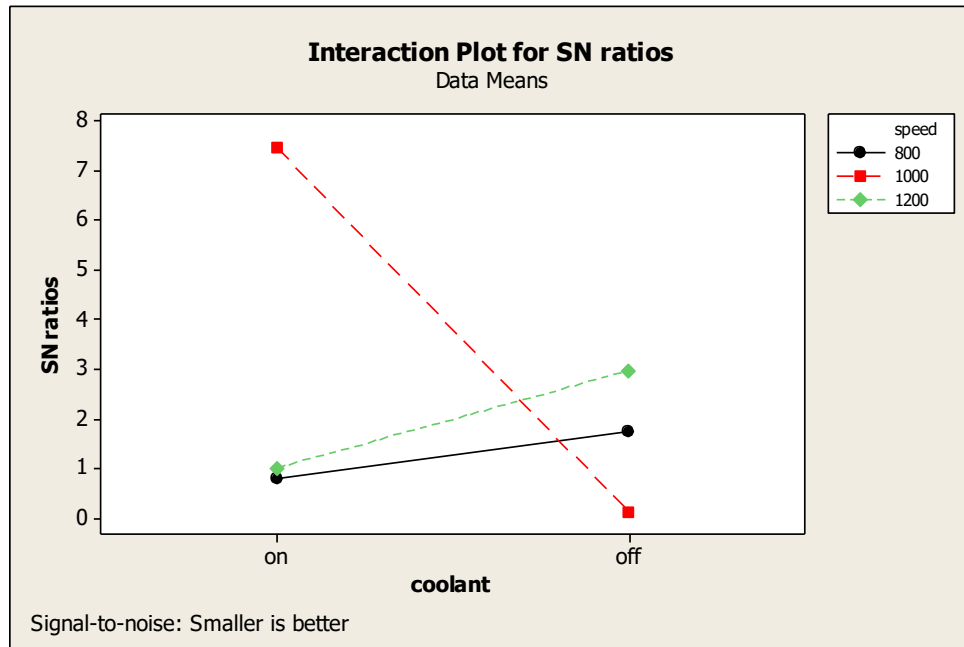


Figure 4.13 Interaction plot (coolant and speed) of S/N ratio for surface roughness.

Estimating the mean

Mean value of surface roughness is given by

$$\mu = \text{feed}_2 + \text{speed}_1 - T$$

Where T is given as mean surface roughness /no. of experiments.

$$\mu = 0.705 + 0.63166 - 0.6633$$

$$\mu = 0.67336$$

Confidence Interval around the Estimated Mean

Confidence Interval around the estimated surface roughness mean

$$C.I. = \sqrt{(F_{v1,v2} \times \frac{Ve}{\eta_{eff}})}$$

Where $F_{\alpha, v1, v2}$ = F ratio

$$\alpha = \text{risk (0.05)}$$

$$\text{confidence} = 1 - \alpha$$

$$v1 = \text{dof for mean which is always } = 1$$

$v_2 = \text{dof for error}$ $V_e = \text{Variance for error}$

$\eta_{\text{eff}} = \text{number of test under that condition using the participating factors}$

$\eta_{\text{eff}} = N / (1 + \text{dof feed, speed}) = 18 / (1 + 2 + 2) = 3.6$

$$C.I. = \sqrt{\left(4.67 \times \frac{0.0227}{3.6}\right)}$$

C.I. = 0.1716

So the confidence interval level around the surface roughness is given by 0.67336 ± 0.1716 .

4.5 Diametrical Deviation

Diameter of holes drilled in CFRP was measured using profile projector and diametrical deviation was calculated using the relation

Diametrical deviation = Desired diameter - actual diameter

Figure 4.14 depicts the process of measuring the hole diameter using profile projector

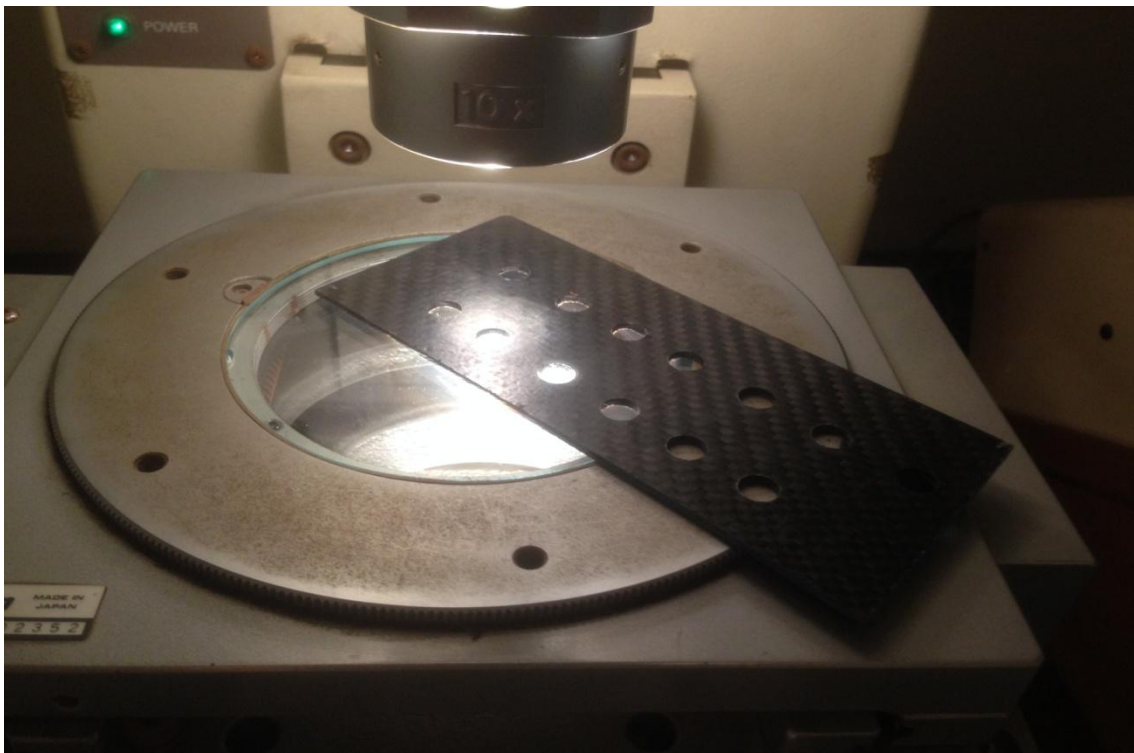
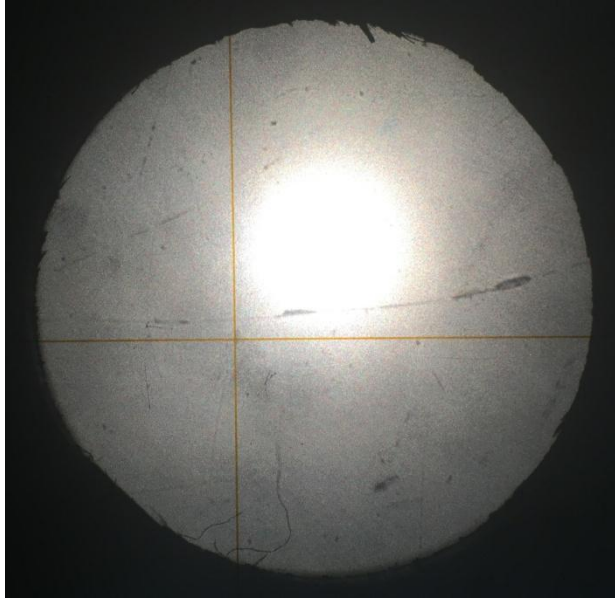
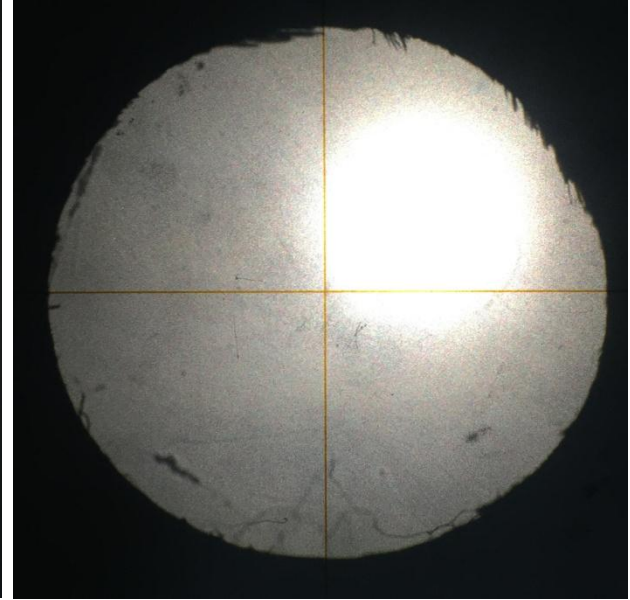


Figure 4.14 Measurement of hole diameter using profile projector



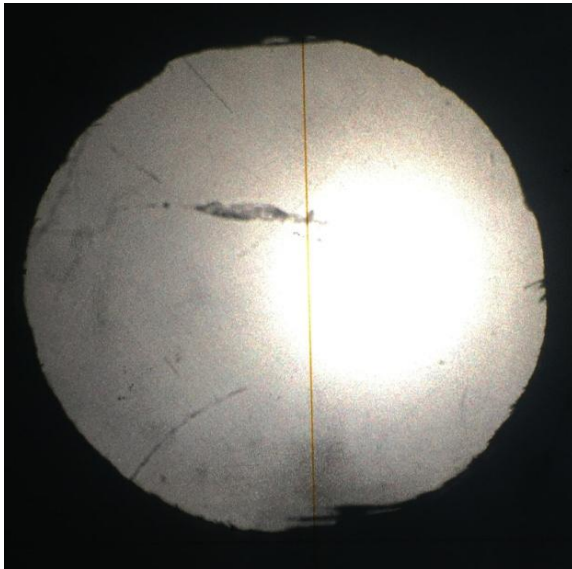
1

coolant-on, tool- twist drill ,
speed -800 rpm , feed- 10 mm/min



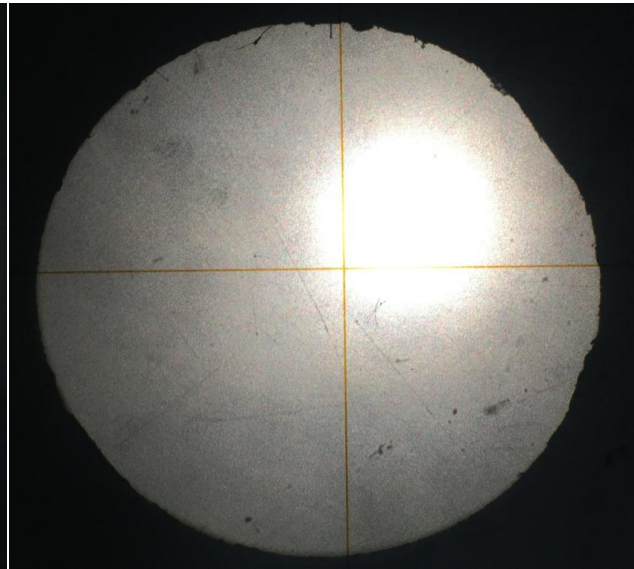
2

coolant-on, tool- twist drill ,
speed -1000 rpm , feed- 15 mm/min



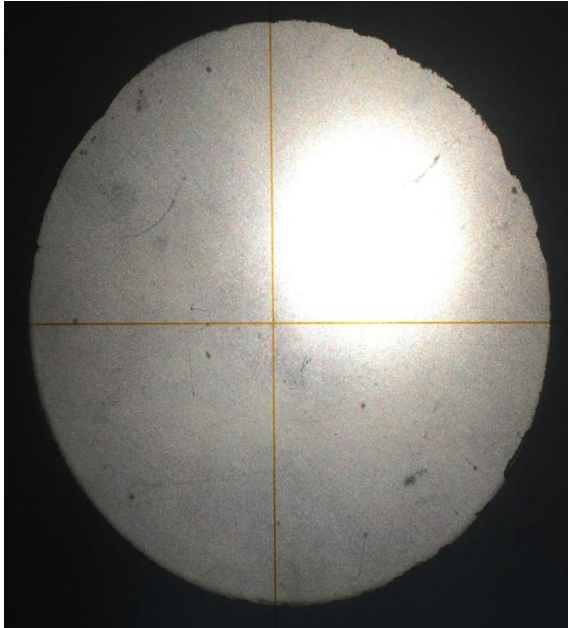
3

coolant-on, tool-twist drill
speed- 1200 rpm, feed- 20mm/min



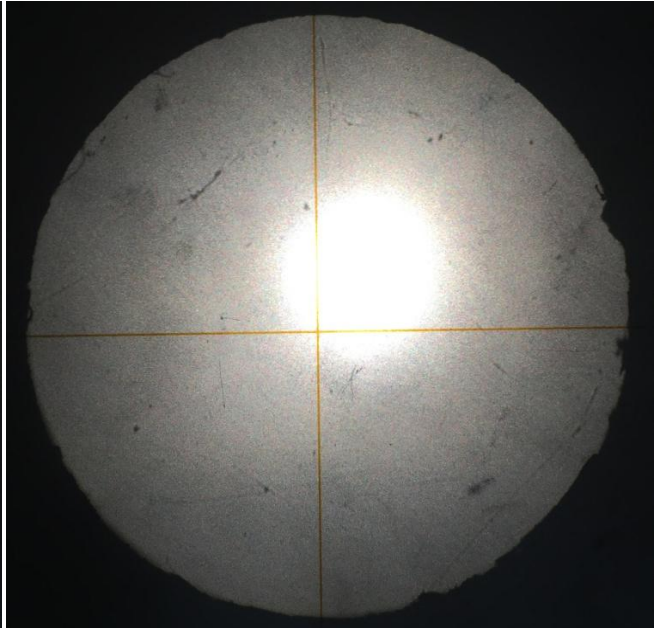
4

coolant-on, tool- brad point drill
speed- 800 rpm, feed- 10mm/min



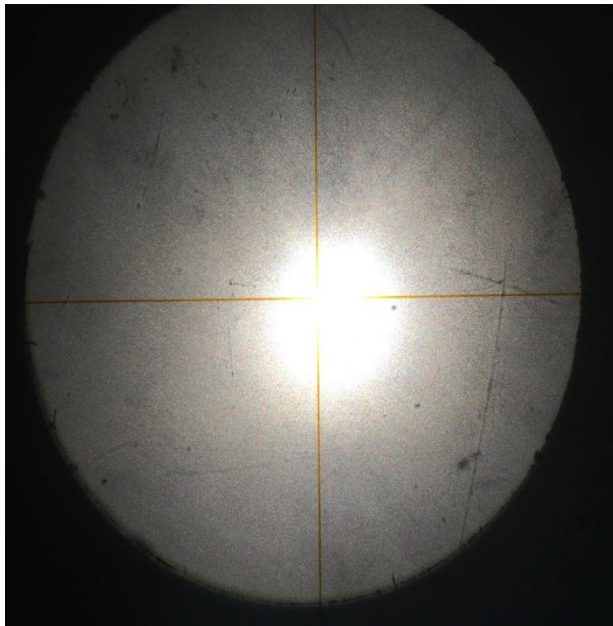
5

coolant-on, tool- brad point drill
speed- 1000rpm, feed- 15mm/min



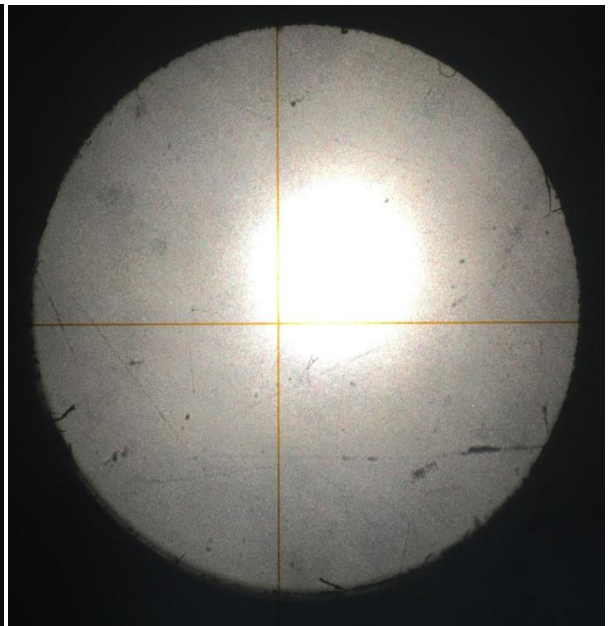
6

coolant-on, tool- brad point drill
speed- 1200rpm, feed- 20mm/min



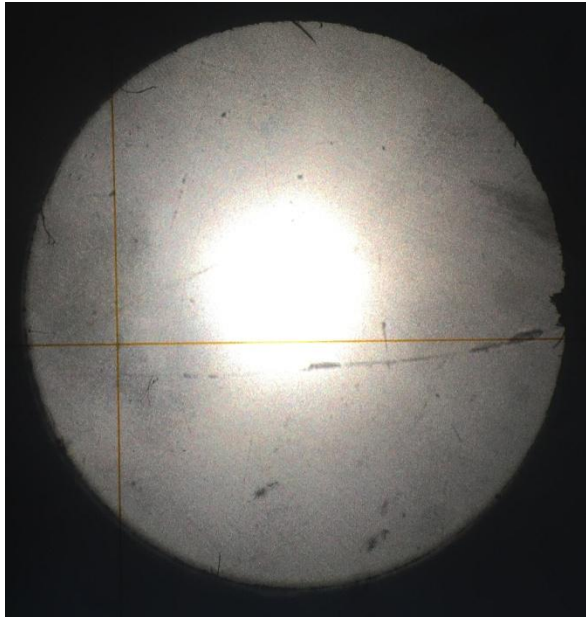
7

coolant-on, tool- end mill
speed-800 rpm, feed-15mm/min



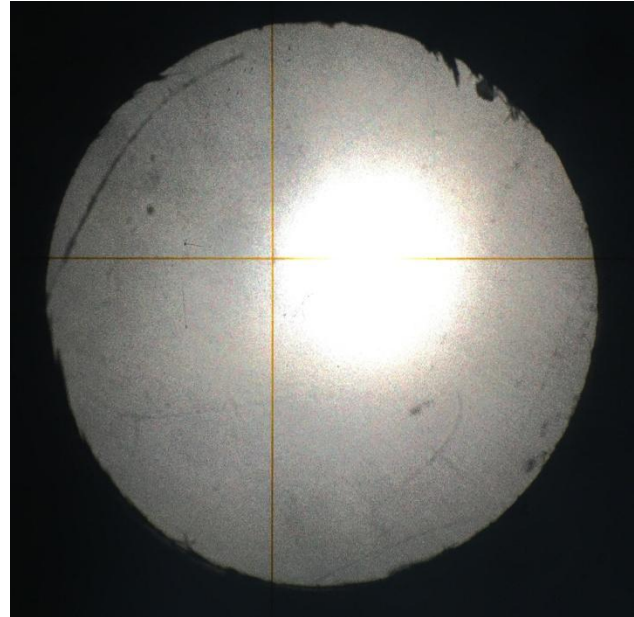
8

coolant-on, tool- end mill
speed-1000 rpm, feed-20mm/min



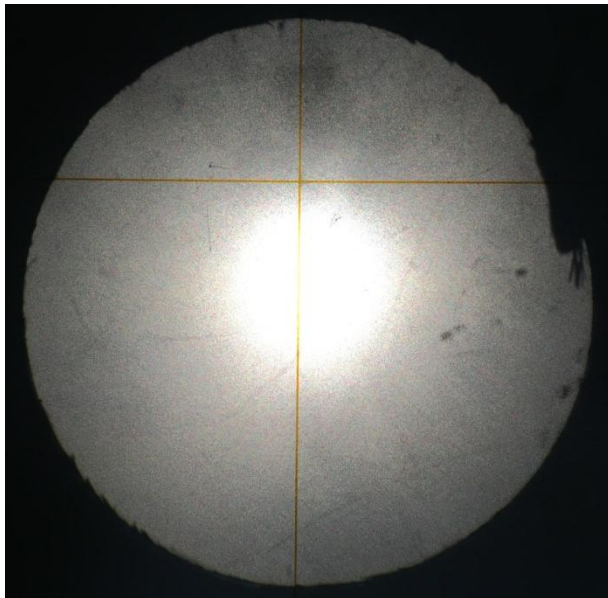
9

coolant-on, tool- end mill
speed-1200 rpm, feed-10mm/min



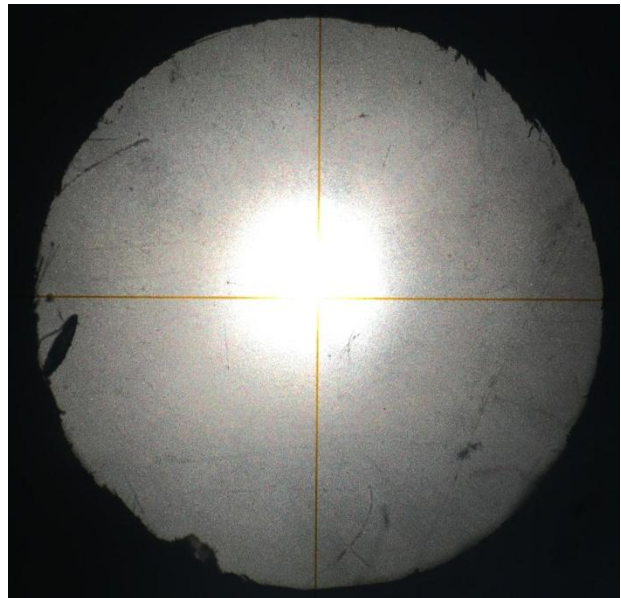
10

coolant-off, tool-twist drill
speed-800 rpm, feed-20mm/min



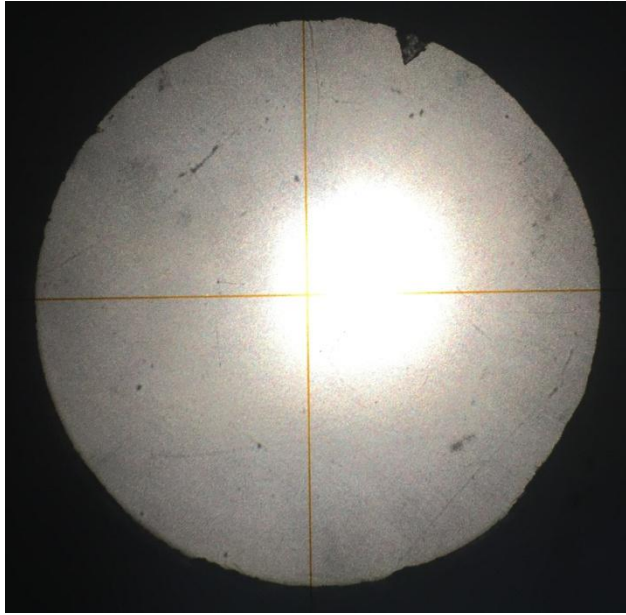
11

coolant-off, tool-twist drill
speed-1000 rpm, feed- 10mm/min



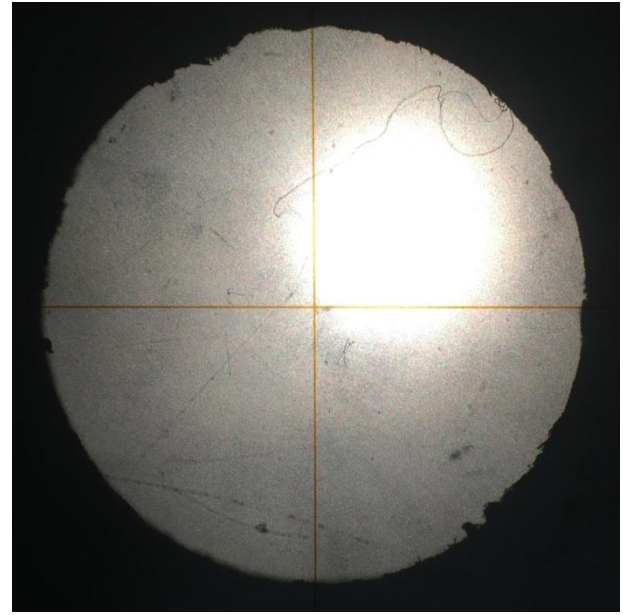
12

coolant-off, tool-twist drill
speed-1200 rpm, feed- 15mm/min



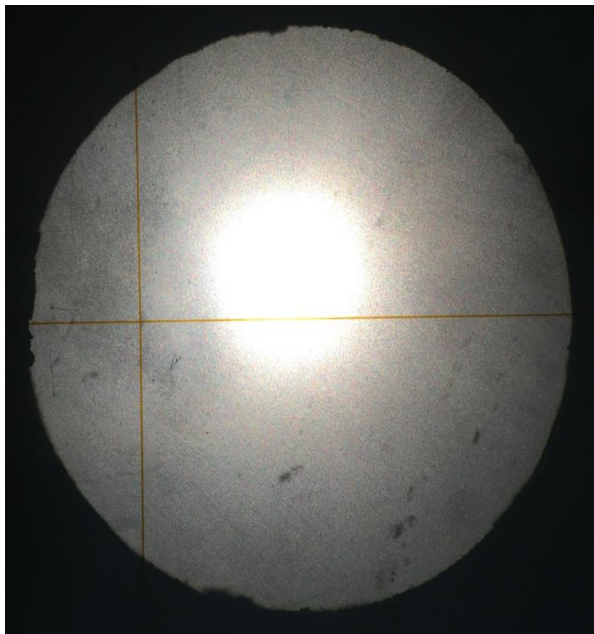
13

coolant-off, tool-brad point drill
speed-800 rpm, feed-15mm/min



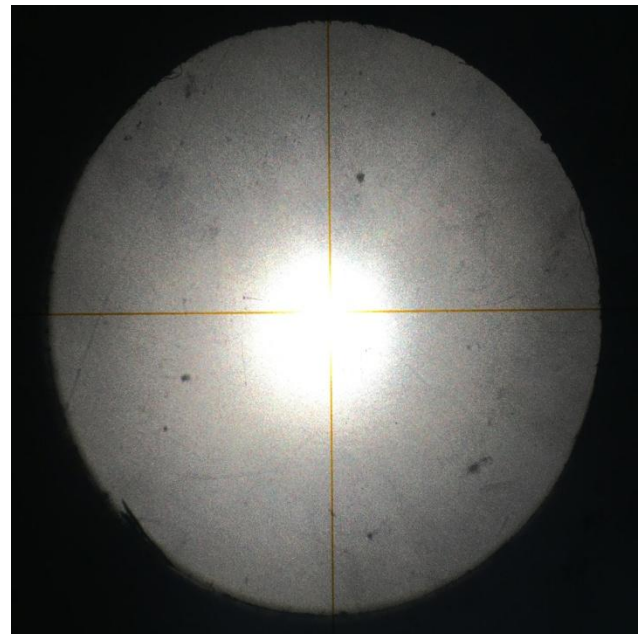
14

coolant-off, tool-brad point drill
speed-1000 rpm, feed-20mm/min



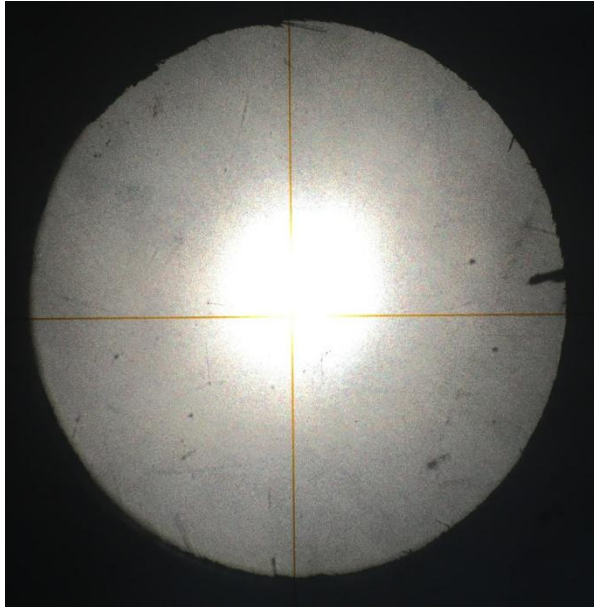
15

coolant-off, tool- brad point drill
speed-1200rpm, feed-10 mm/min



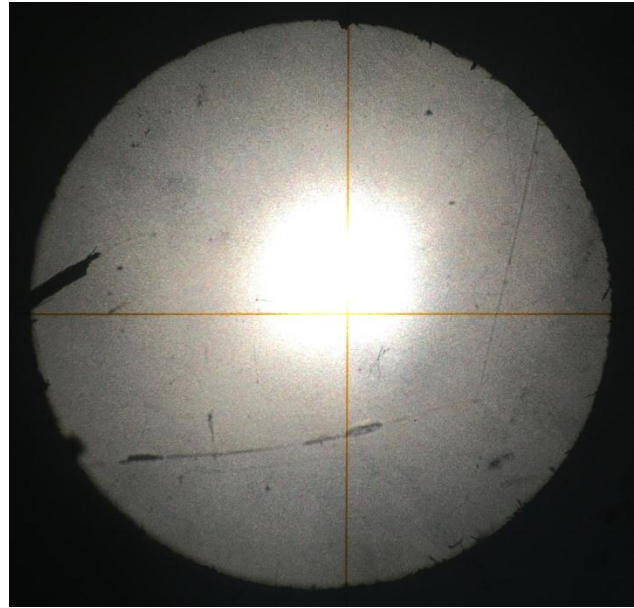
16

coolant-off, tool- end mill
speed-800rpm, feed-20 mm/min



17

coolant-off, tool-end mill
speed-1000rpm, feed-10 mm/min



18

coolant-off, tool-end mill
speed-1200rpm, feed-15 mm/min

Figure 4.15 Images of all the drilled holes as viewed from profile projector

Table 4.16 Results for diametrical deviation and S/N ratio

Exp no.	Coolant	Tool	Speed (RPM)	Feed (mm/min)	Diametrical deviation (mm)		Mean	S/N Ratio(dB)
1	On	Twist drill	800	10	0.0899	0.0931	0.0915	20.770
2	On	Twist drill	1000	15	0.1422	0.1448	0.1435	16.741
3	On	Twist drill	1200	20	0.1289	0.1311	0.1300	17.720
4	On	Brad point	800	10	0.0332	0.0413	0.0385	28.270

5	On	Brad point	1000	15	0.0398	0.0462	0.0430	27.320
6	On	Brad point	1200	20	0.0405	0.0435	0.0370	28.620
7	On	End mill	800	15	-0.0775	-0.0845	-0.0810	23.820
8	On	End mill	1000	20	-0.1118	-0.1182	-0.115	25.780
9	On	End mill	1200	10	-0.0562	-0.0618	-0.0590	30.570
10	Off	Twist drill	800	20	0.0495	0.0495	0.0480	26.370
11	Off	Twist drill	1000	10	0.0917	0.0917	0.0905	23.860
12	Off	Twist drill	1200	15	0.0335	0.0335	0.0325	27.750
13	Off	Brad point	800	15	0.0523	0.0523	0.0499	25.020
14	Off	Brad point	1000	20	0.0764	0.0764	0.0743	25.570
15	Off	Brad point	1200	10	0.0606	0.0606	0.0589	24.600
16	Off	End mill	800	20	-0.0864	-0.0864	-0.0830	27.610
17	Off	End mill	1000	10	-0.0331	-0.0331	-0.0300	30.411
18	Off	End mill	1200	15	-0.0252	-0.0252	-0.0225	32.890

Analysis of variance- Diametrical deviation

The results for diametrical deviation were analyzed using ANOVA for identifying the significant factors. Analysis of Variance was calculated using MINITAB software and the results of ANOVA are presented in table 4.17. The p value was observed to find significance of each factor and their interaction. Factors having p value smaller than 0.05 are assumed to be significant.

Table 4.17 ANOVA table of means for diametrical deviation

Source	DOF	Seq SS	Adj MS	F	P	% contribution	Status
Coolant	1	0.0000	0.0000	0.01	0.932	0.013	Insignificant
Tool	2	0.0773	0.0386	65.61	0.015	85.68	Significant
Speed	2	0.0018	0.0002	0.38	0.725	0.49	Insignificant
Feed	2	0.0008	0.0001	0.18	0.850	0.23	Insignificant
Coolant*tool	2	0.0093	0.0046	7.92	0.112	10.29	Insignificant
Coolant*feed	2	0.0004	0.0007	1.23	0.449	1.59	Insignificant
Tool*speed	4	0.0029	0.0008	1.24	0.491	1.61	Insignificant
Error	2	0.0011	0.0005				
Total	17	0.0941					

$$S = 0.0242792 \quad R\text{-Sq} = 98.75\% \quad R\text{-Sq(adj)} = 89.35\%$$

From table 4.17 showing the ANOVA results for diametrical deviation the factor affecting the output significantly can be found. It has been depicted that tool type is the lone factor affecting the diametrical deviation of the holes. p value of tool type is 0.015 (which is less than 0.05) and has a percentage contribution of about 85.68%. All other factors under consideration are having trivial effect on the output parameter under consideration.

Table 4.18 Response table for means for diametrical deviation

Level	Coolant	Tool	Speed	Feed
1	0.02539	0.08933	0.01065	0.03173
2	0.02429	0.05027	0.03438	0.02757
3		-0.0650	0.02948	0.01522
Delta	0.00110	0.15442	0.02373	0.01652
Rank	4	1	2	3

Table 4.18 shows the ranks of main factors in terms of their relative significance. Table shows that 1st rank has been assigned to tool type factor which has a significant effect on the hole diameter. 2nd rank has been given to spindle speed which is then followed by feed rate and then by coolant.

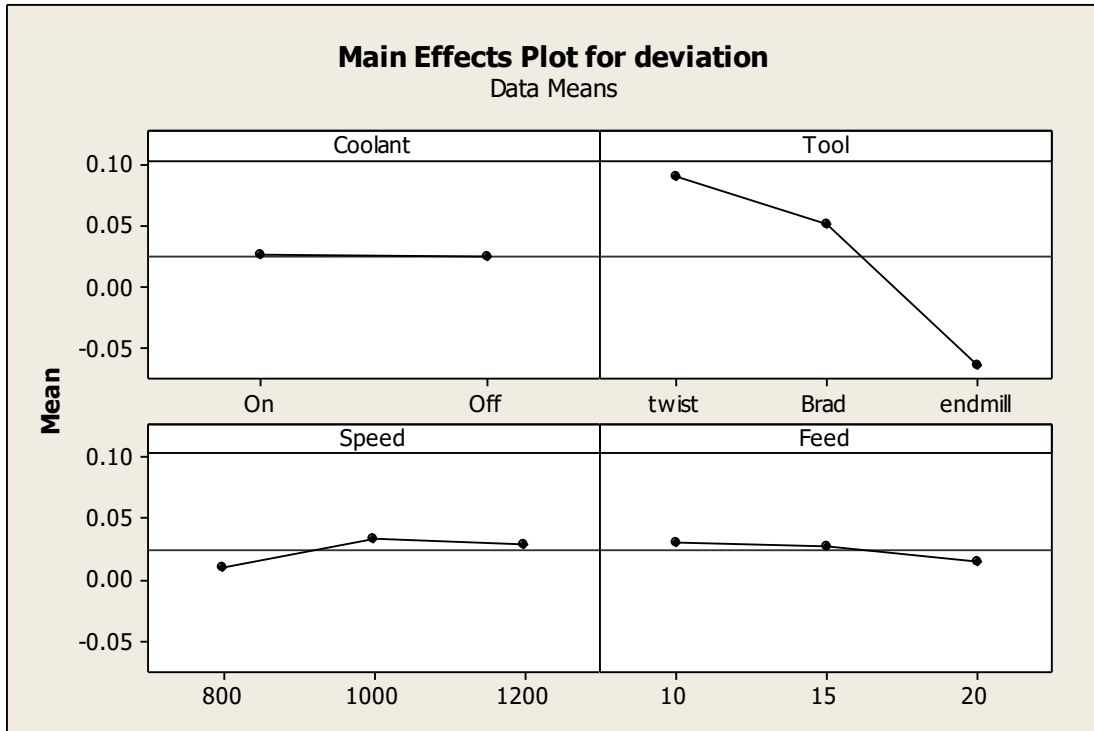


Figure 4.16 Main effect plots of means for diametrical deviation

Fig 4.16 depicts the main effect plots of four input factors viz spindle speed, feed, coolant and tool type. From the plot it is observed that coolant is found to have minimal effect on diametrical deviation with low deviation occurring when coolant is turned off. Tool type as depicted in the plot is having a large impact on the hole deviation as also calculated in ANOVA. Maximum hole diameter deviation is seen to occur while drilling with twist drill while drilling with brad point drill leads to a minimal diametrical deviation. Spindle speed is observed to have rather little effect on diametrical deviation with a minimum deviation taking place at spindle speed of 800 rpm. In the same way feed rate has trivial effect on deviation with low diametrical deviation taking place at a feed rate of 15 mm/min.

Fig 4.17 shows the interaction plots for combined effect of various factors on diametrical deviation.

However on carefully studying the plots it has been concluded that no interaction has a major role to play in the variation of hole diameters.

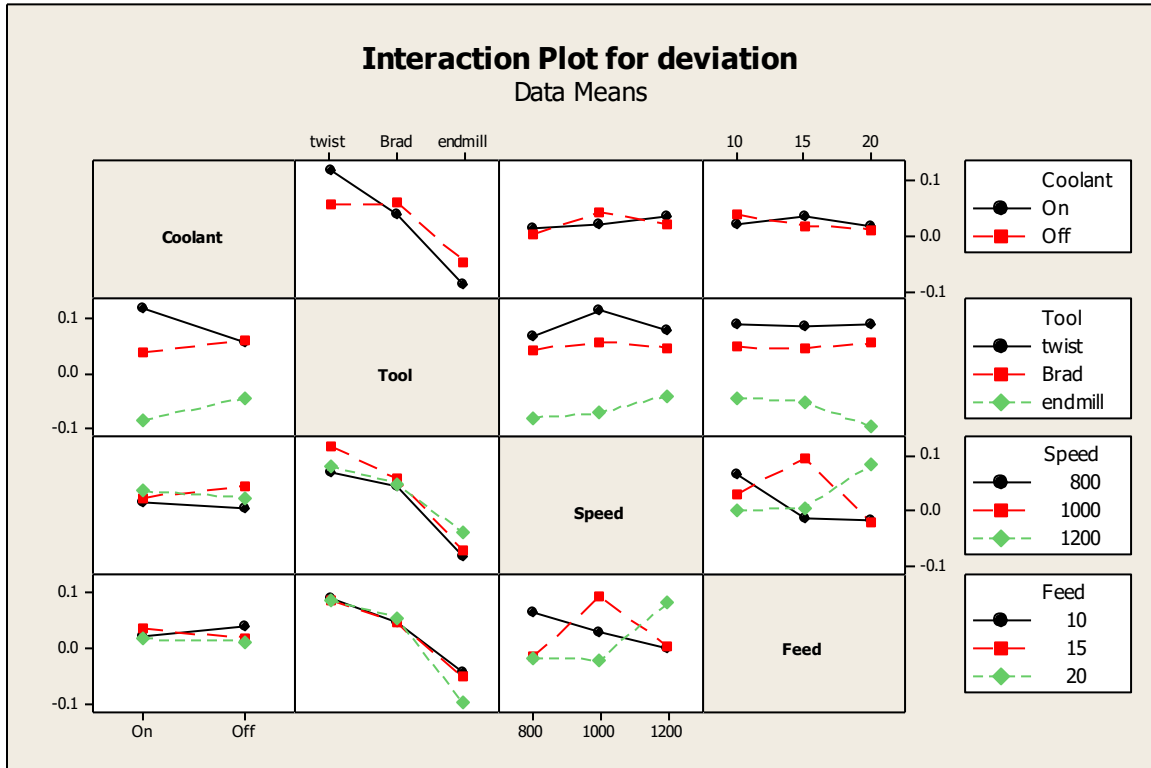


Figure 4.17 Interaction plot of means diametrical deviation

Results for S/N Ratio of Diametrical deviation

The S/N ratios have been calculated to identify the major contributing factors and interactions that cause variation in the surface roughness.

Diametrical deviation is lower the best characteristic which is given by:

$$S/N_{LB} = -10 \log \left[\frac{\sum_1^r y^2}{r} \right]$$

where:

y is observed value of entry delamination factor for a given experiment

r is the number of repetitions performed for a given experiment.

From table 4.19 showing the ANOVA results for S/N ratio for diametrical deviation the factor affecting the output significantly can be found. It has been calculated that tool type is the most significant factor affecting S/N ratio with percent contribution of 42.28%. Coolant has been seen to have significant effect on variation having percent contribution of 22.49%. In addition to main

factors interaction of coolant and tool has also been seen to be significant with p value 0.018 and percent contribution 28.99%.

Table 4.19 ANOVA table of S/N ratio for diametrical deviation

Source	DOF	Seq SS	Adj MS	F	P	% Contribution	Status
Coolant	1	33.266	33.266	41.64	0.023	22.49	Significant
Tool	2	125.358	62.679	78.46	0.013	42.28	Significant
Speed	2	14.782	3.241	4.06	0.198	2.19	Insignificant
Feed	2	4.127	1.171	1.47	0.406	0.79	Insignificant
Coolant*tool	2	85.775	42.888	53.69	0.018	28.99	Significant
Coolant*feed	2	25.983	2.575	3.22	0.237	1.73	Insignificant
Tool*speed	4	9.571	2.393	3.00	0.266	1.62	Insignificant
Error	2	1.598	0.799				
Total	17	300.460					

$$S = 0.893770 \quad R-Sq = 99.47\% \quad R-Sq(adj) = 95.48\%$$

Table 4.20 ranks main factors on basis of their variation in S/N ratio. It has been concluded that tool has maximum variation in between its levels followed by coolant. Spindle speed and feed rate are ranked third and fourth respectively.

Table 4.20 Response table for S/N ratios for diametrical deviation

Level	Coolant	Tool	Speed	Feed
1	24.40	22.20	25.31	26.41
2	27.12	26.57	24.95	25.59
3		28.51	27.02	25.28
Delta	2.72	6.31	2.08	1.14
Rank	2	1	3	4

Fig 4.18 shows the effect of main factors on S/N ratio. For coolant it has been observed that when coolant is turned off it leads to a high S/N ratio as compared to when it is turned on. Machining with end mill results in a high S/N ratio as compared with other levels, with minimum S/N ratio being observed for twist drill. Small variation in S/N ratio is observed at all three levels of spindle speed with maximum occurring at 1200 rpm. Similar case has been

observed in feed rate with maximum S/N ratio obtained at 10 mm/min and minimum at 20 mm/min. Interaction plot of coolant and tool vs SN ratio has been shown in figure 4.19 which has a significant effect on S/N ratio as shown in ANOVA table 4.19 with percent contribution of 28.99%

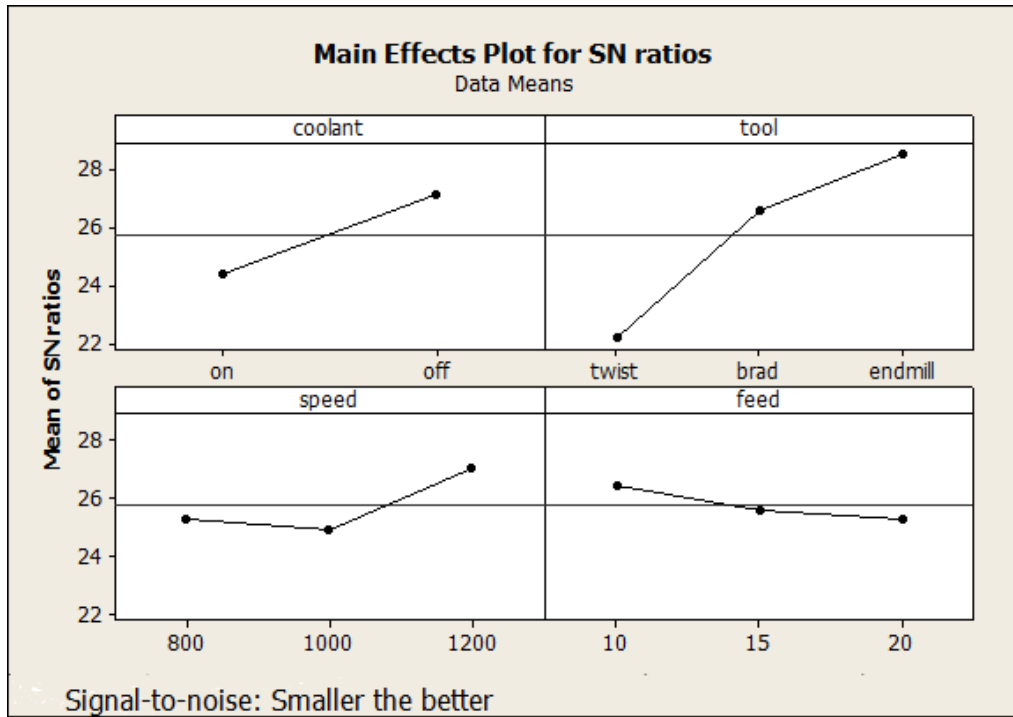


Figure 4.18 : Main effect plots of S/N ratio for diametrical deviation

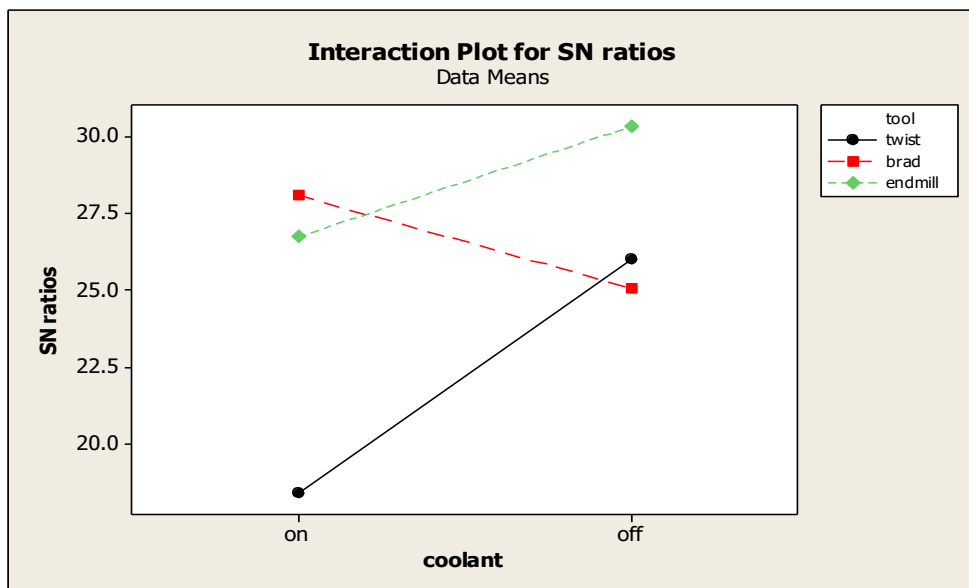


Figure 4.19 Interaction plot (coolant and tool) of S/N ratio for diametrical deviation

Estimating the mean

Mean value of diametrical deviation is given by

$$\mu = \text{tool}_2$$

Where T is given as mean diametrical deviation /no. of experiments.

$$\mu = 0.05027$$

Confidence Interval around the Estimated Mean

Confidence Interval around the estimated diametrical deviation mean

$$C.I. = \sqrt{(F_{v1,v2} \times \frac{Ve}{\eta_{\text{eff}}})}$$

Where $F_{\alpha, v1, v2}$ = F ratio

$$\alpha = \text{risk (0.05)}$$

$$\text{confidence} = 1 - \alpha$$

$v1$ = dof for mean which is always =1

$v2$ = dof for error

$Ve = (SS_{\text{total}} - SS_{\text{significant factors}}) / (\text{total dof} - \text{dof of significant factors})$

η_{eff} = number of test under that condition using the participating factors

$$\eta_{\text{eff}} = N / (1 + \text{dof tool}) = 18 / (1 + 2) = 6$$

$$C.I. = \sqrt{(4.54 \times \frac{0.0005}{6})}$$

$$C.I. = 0.019$$

So the confidence interval level around the diametrical deviation is given by 0.05027 ± 0.019 .

Chapter 5

Conclusions

5.1 Entry Delamination factor

- Tool type has greatest effect on entry delamination factor. Using brad point drill results in lowest value of entry delamination factor. Highest S/N ratio has been observed in case on brad point drill concluding that it has least effect on variation in the process.
- On increasing the spindle speed, entry delamination factor increases linearly. Spindle speed significantly influences S/N ratio. On increasing spindle speed S/N ratio decreases linearly showing that variation in process increases with increase in spindle speed.
- Interaction of coolant and feed has next significant contribution on mean and variation of entry delamination factor with minimum entry F_d occurring when coolant is off and feed rate is 20 mm/min.
- Lowest entry delamination is seen while machining with brad point drill, spindle speed of 800rpm and feed rate of 20 mm/min.
- With 95% confidence interval mean value of entry delamination factor is given by 1.05373 ± 0.02334 .

5.2 Exit Delamination factor

- Drilling using twist drill results in lowest mean value and variation in exit delamination factor. End mill results in highest mean value and high variation in exit delamination factor.
- When coolant is off, low mean value and low S/N ratio of exit delamination factor has been observed.
- Lowest exit delamination is seen while machining with twist drill, at 80 rpm spindle speed, 10 mm/min feed rate and when coolant is turned on.
- With 95% confidence interval mean value of exit delamination factor is given by 1.246 ± 0.0662 .

5.3 Surface Roughness

- Spindle speed has most significant effect on surface roughness of hole. Low spindle speed results in a high surface finish. On increasing spindle speed surface roughness increases.
- Feed rate of 15 mm/min results in a high surface finish. On increasing or decreasing feed rate from 15 mm/min surface roughness increases.
- High surface finish is obtained when machining is done at 800 rpm spindle speed, feed rate is set at 15 mm/min, coolant is turned on and tool used is brad point drill.
- With 95% confidence interval mean value of surface roughness is given by 0.67336 ± 0.1716 .

5.4 Diametrical Deviation

- Tool type is the lone factor affecting diametrical deviation of hole. Brad point drill results in lowest deviation from desired value.
- Twist drill leads to highest deviation from desired hole diameter.
- End mill shows a highest value of S/N ratio thereby indicating that it has significant effect on reducing variation in process. It is followed by brad point drill and twist drill in order of their decreasing S/N ratio.
- When coolant is turned off it resulted in high S/N ratio thereby concluding that it lowers variation in process.
- Machining with brad point drill at 800 rpm spindle speed, feed rate of 20 mm/min and without coolant gives least deviation from desired diameter.
- Holes obtained by twist drill and brad point drill were under size as according to Shyha et al(2010)⁵.
- With 95% confidence interval, mean value of diametrical deviation is given by 0.05027 ± 0.019 .

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List of Publications

- [1.] Shobhneek Singh, Dr. Vivek Jain, Dr. Dheeraj Gupta," Experimental Study on Drilling of Carbon Fibre Reinforced Plastics(CFRP)" Part B: Journal of Engineering Manufacture.

under review