Chapter 4
Experimental Work

CHAPTER 4
EXPERIMENTAL WORK

This chapter deals with the experimental investigation of DSS 2205 under environmentally friendly machining and using optimization techniques for designing experiments in drilling operations. All the experimental work is divided into three phases. The first phase of experimental work was carried out under dry and wet conditions, and the second phase of experimental work was carried out under dry, MQL, and LCO_2 conditions. Finally, experimental work was carried out in the third phase under a hybrid MQL-LCO_2 condition.

4.1 Experimental Setup

4.1.1 CNC Machine

In order to precisely remove materials from a work piece, CNC milling machines are machine-operated cutting tools that are programmed and managed by CNC systems. Figure 5.1 display the CNC machine's visual representation. A specific item or product that was designed using Computer-Aided Design (CAD) software in a CNC machine. All of the experimental work for the current study was completed on a CNC machine that also performed drilling operations. The specification of the CNC machine is also given in table 4.1.

Table 4.1: Specification of CNC machine

1	Tool holder	SK30DIN69871
2	Travel in X/Y/Z	350/250/300 mm
3	Distance spindle nose	120-420 mm
4	Work feed	0-10 m/min
5	Feed force X/Y/Z	3000
6	Clamping area	520 * 300 mm
7	Max. table load	100 kg
8	Max. Speed	10000 U/min
9	Max torque	24 Nm
10	Number of tool station	20
11	Tool change time	2.5 s
12	Max tool diameter	80 mm
13	Max tool length	200 mm

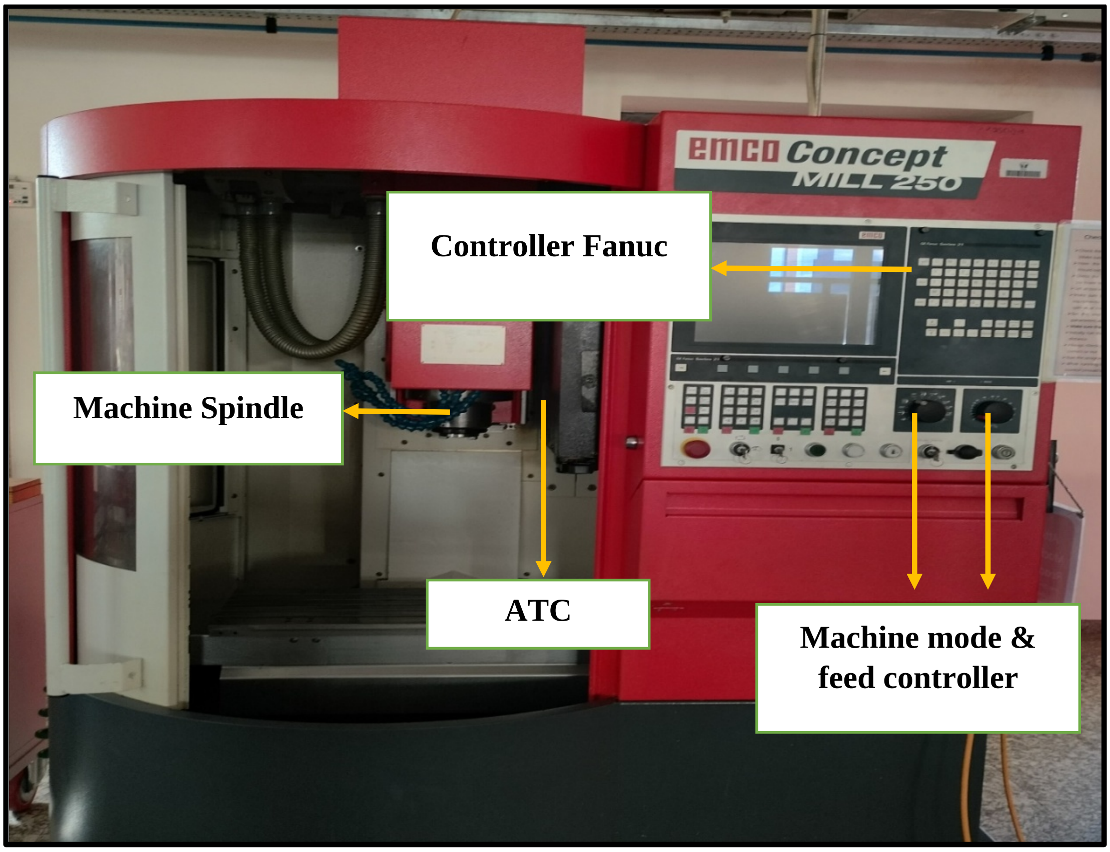


Fig. 4.1: CNC Machine

4.1.2 Work piece Material

The work piece material used in this research was duplex stainless steel (DSS) 2205 with a 5 mm thickness, shown in figure 4.2. Due to duplex stainless steel's excellent combination of good mechanical properties and high corrosion resistance, it is widely used in industrial fields such as the production of seawater heat exchangers and chemical containers for the high concentration chloride environment. Table 4.2 shows the chemical composition of DSS2205.

Table 4.2 Chemical composition of DSS 2205

Element	Carbon	Chromium	Nickel	Molybdenum	Nitrogen	Others
%	0.030%	21-23%	5.5-6.5 %	3.1-35%	0.18-0.20%	S-0.001-0.020% P-0.030%, Si-1%

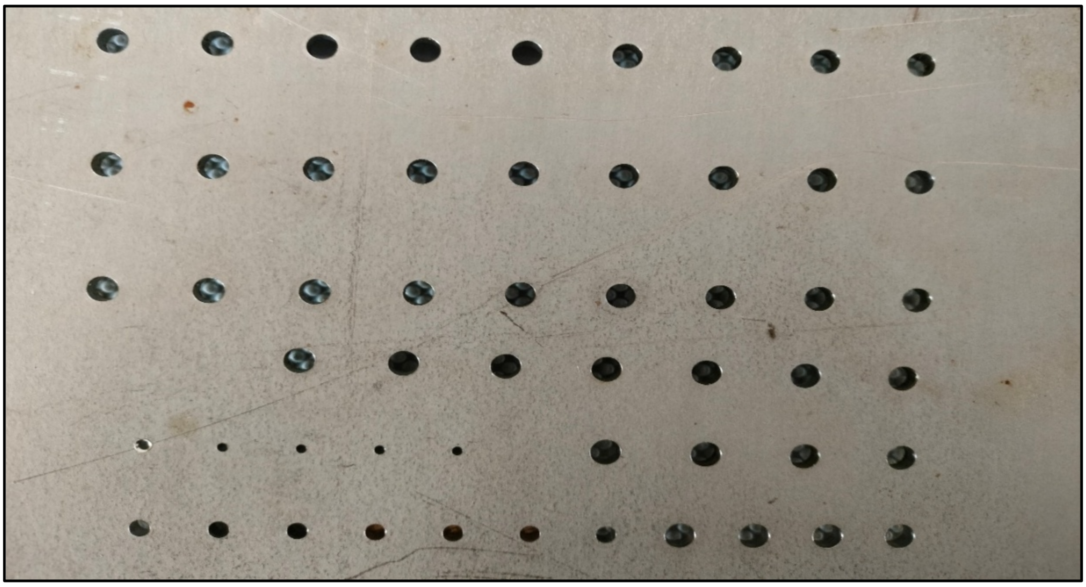


Fig. 4.2: Machined work piece

4.1.3 Cutting Tool and Tool Holder

4.1.3.1 Cutting Tool

The cutting tool material used in this experimental study was a TiAlN-coated solid carbide drill with a drill diameter of 6mm. Figure 4.3 shows an image of cutting tool material.

Descriptions of the cutting tool

Tool material- Solid carbide, Nominal diameter- 6 mm, Coating- TiAlN, through coolant- No Flute, Type of product- High-performance drill, HRC- 55.

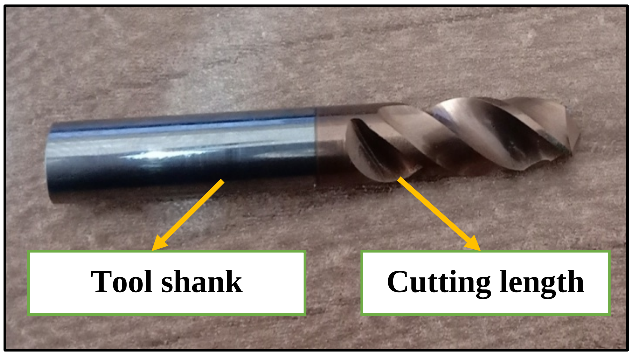


Fig. 4.3: Cutting tool

4.1.3.2 Tool Holder

The cutting tool holder used in the specification of ISO-designated SK 30 DIN69871-A, is presented in Figures 4.4 &4.5. The tool holder is made of casehardened steel with 58 HRC. The classic milling spindle interface DIN ISO 7388-1 (formerly 69871) sets itself apart with its incredibly durable construction. It may be used for everything from light-duty roughing to heavy-duty machining. A second pull stud is used to pull the tool holder into the milling spindle. The tapered contact is used for cantering. Therefore, applications with a spindle speed of up to 12,000 rpm are best suited for the DIN ISO 7388-1 (formerly 69871) interface.

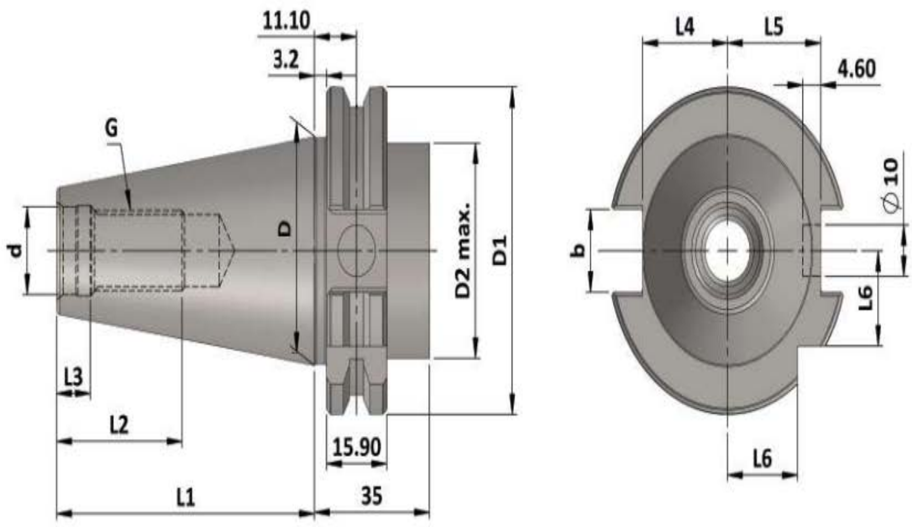


Fig. 4.4: Geometry of tool holder

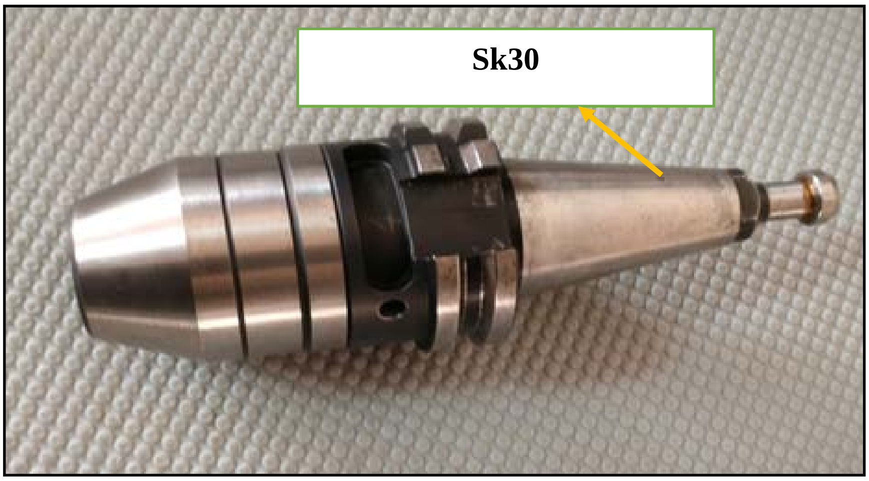
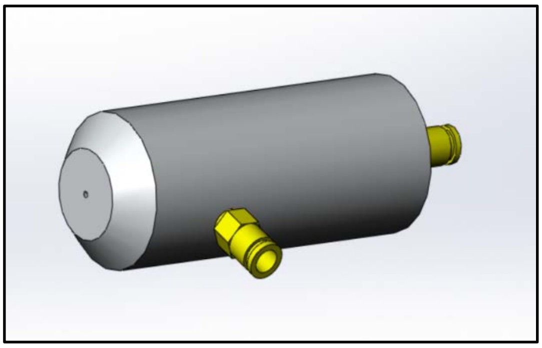


Fig. 4.5: Shows the tool holder

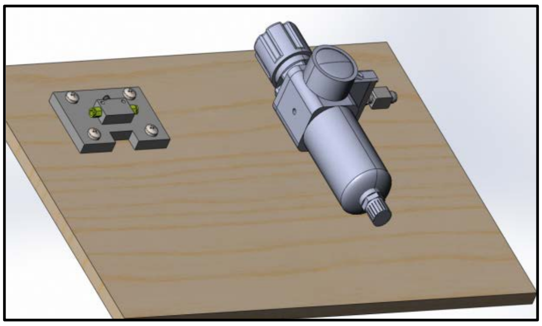
4.1.4 Minimum Quantity of Lubrication (MQL)

A little amount of environmental friendly lubricant (mainly vegetable oil combined with air) is used in place of water and mineral oil-based cutting fluids in the MQL micro lubrication technique.



(a)

(b)



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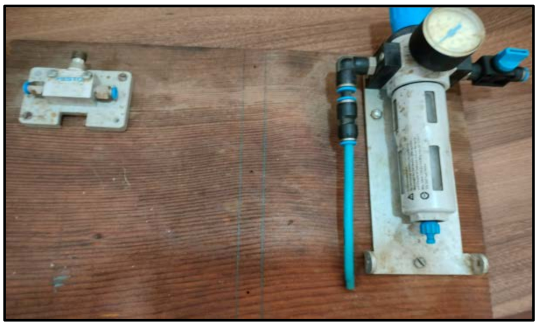

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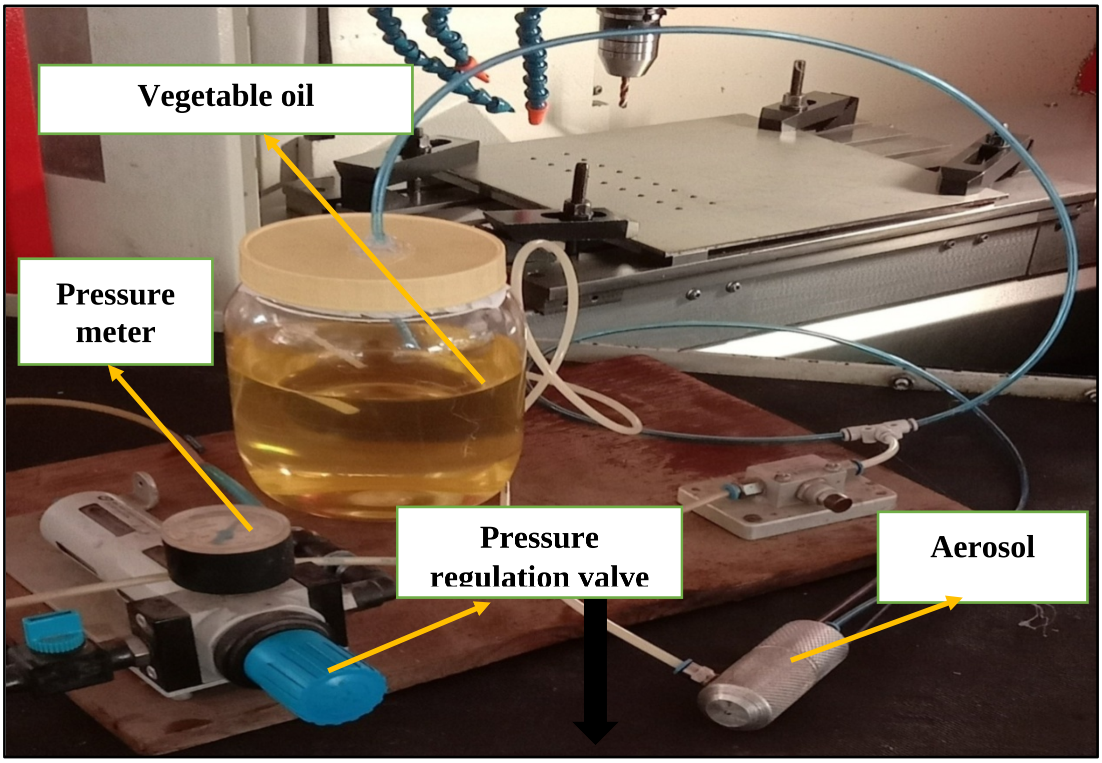

Fig. 4.6: (a, b, c, d, e) MQL setup

In the current investigation lubricant at 1.5 bar air pressure was transported into the machining zone for improving the machinability. Those parameter values are may be easily modified by an airflow regulator and control unit of the system. The design of the MQL setup is shown in figure 4.6.

The specifications of the MQL setup are presented in the table.

Table 4.3: Specification of MQL setup

Characteristics	**Description**
Lubricant use	Vegetable oil
Air pressure	1.5 bar- 3bar
Reservoir capacity	1.5 litre
No. of pumping element	1
Diameter of nozzle	1mm

Compressed air is delivered into the mixing chamber during the MQL process via a solenoid valve and moisture control valve. Lubricant oil from the oil tank entered a mixing chamber at the same time. Furthermore, the mixing chamber effectively blended compressed air and oil. In order to lower the cutting temperature and increase the machinability of DSS 2205, mixed coolant was also delivered into the machining zone through the nozzle.

The characteristics of vegetable oil are presented in table 4.4.

Table 4.4: Characteristics of vegetable oil

Properties	**Description**
Appearance	Golden yellow
Solubility	Not soluble in water
Kinetic viscosity (mm^2/s)	29
Density	0.919
Viscosity index	100-200
Shear stability	Good

Oxidation stability	Medoicre
Hydrolytic stability	Poor

Vegetable oil is a non-toxic, non-polluting lubricant. It doesn't cause the operator's skin to irritate, discolour, or smoke. It has remarkable lubricating properties and is created from all-natural components. By reducing the heat generated by the tool and work area, excellent anti-friction and severe pressure properties can lead to considerably longer tool life and better surface finishes.

4.1.5 Liquid Carbon dioxide (LCO2) Setup

In LCO_2 machining, liquid carbon dioxide is used as a coolant, which is shown in figure 4.7. For improving the machinability through reducing the cutting temperature. Machining with LCO_2 is cryogenic machining. In cryogenic machining, different types of child gases are used for improving machinability.

In the current investigation, LCO_2 cooling techniques are implemented for improving the machinability of DSS 2205. LCO_2 is an environmental friendly machining technique. The demand for renewable and biodegradable cutting fluids is rising daily as a result of environmental concerns, rising contamination, and pollution legislation. One of the most recent cost-effective and environmentally favourable methods to increase machinability is environmental-friendly machining.
The specification of the LCO_2 setup is given in table 4.5.

Table 4.5: Specification of LCO_2 setup

Characteristics	**Description**
Cryogenic gas	Liquid carbon dioxide (LCO_2)
Pressure of cylinder	25 bar
The flow rate of gas	18 l/m
No. of pumping element	1
Diameter of nozzle	2.5 mm

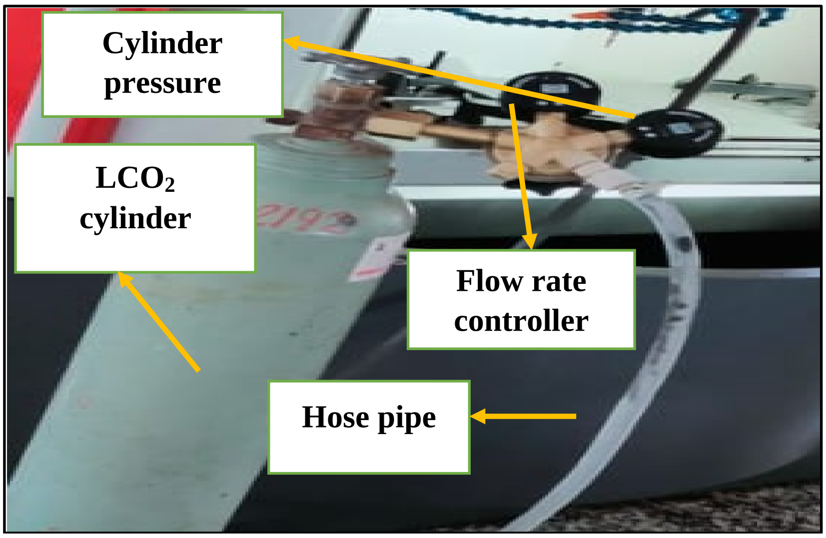

Fig. 4.7: LCO_2 Setup

The characteristics of LCO_2 gas are presented in table 4.6.

Table 4.6:Characteristics of LCO_2 gas

Properties	**Description**
Flammable	No
Melting point	-55.5^o C
Boiling point	-78.5^o C
Density	1.97 g/ml

4.2 Measuring Instrument

4.2.1 Surface Roughness Tester

When determining whether a surface is suitable for a certain function, roughness is a key factor. Generally speaking, rough surfaces deteriorate faster than smoother ones. Rougher surfaces can help with adhesion but are typically more prone to corrosion and cracking. To quickly and precisely determine a material's surface texture or surface roughness, a roughness tester is utilized. A roughness tester displays the mean roughness value (Ra) and the measured roughness depth (R_z) in microns (m). Applying a roughness filter is necessary to measure the roughness of a surface. Different roughness filters should be used, according to various international standards and surface texture or surface finish demands. Figure 4.8 shows the surface roughness tester.

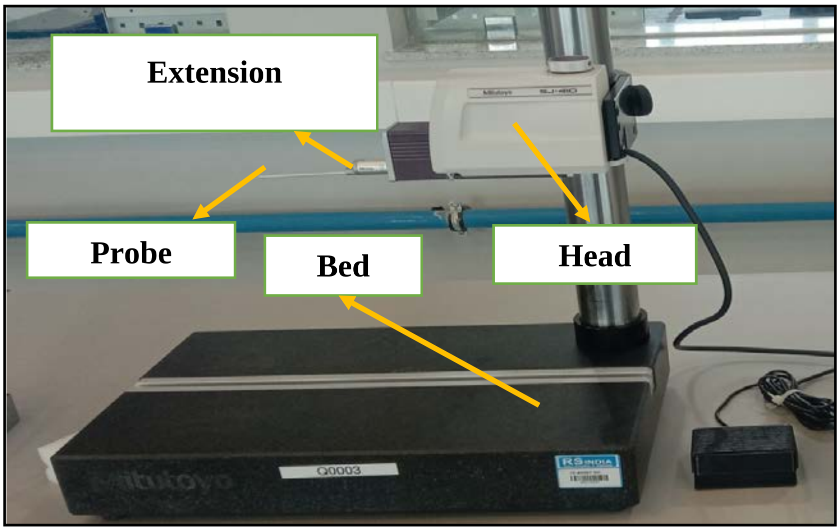

Fig. 4.8: Surface roughness tester

4.2.2 Coordinate Measuring Machine (CMM)

A coordinate measurement machine (CMM) is a device that analyses discrete points on the surface of real-world objects to determine their geometry. Although there are optical and white light sensors, mechanical and laser sensors are the most often used probe types in CMM. The probe location may be managed manually by an operator or it may be managed by a computer, depending on the machine. In a three-dimensional Cartesian coordinate system, a CMM typically specifies a probe's position in terms of its displacement from a reference position (i.e., with XYZ axes).Many machines allow the probe angle to be adjusted in addition to the X, Y, and Z axes, enabling the measurement of surfaces that would otherwise be inaccessible.

In manufacturing and assembly procedures, CMMs are frequently used to test a product or assembly against the design intent. The distance between features can be confirmed using the measured points. They can also be used to build geometric features for GD&T such as cylinders, planes, and others so that properties like roundness, flatness, and perpendicular can be evaluated. Figure 4.9 shown CMM setup.

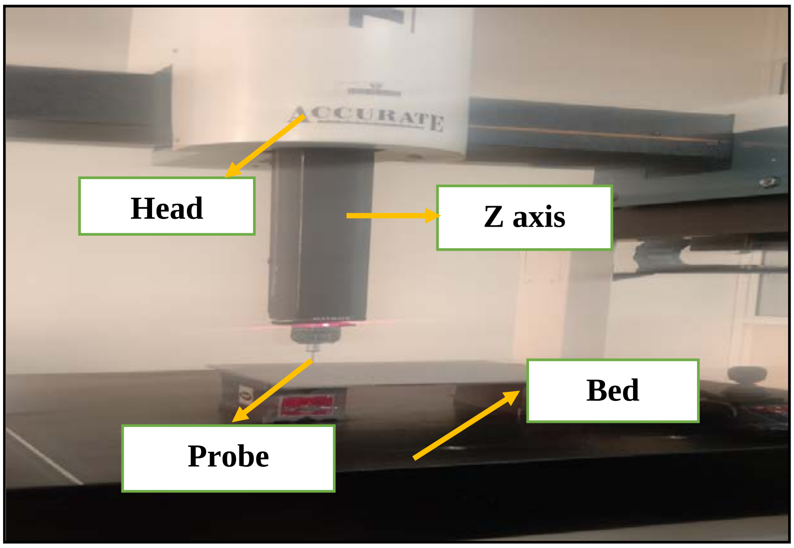

Fig. 4.9: Setup of CMM

4.2.3 Visible Tool Wear analysis

For a general analysis of the tool, wear is carried out by using tool Pre-setting Devices in the present investigation. In the current investigation, the drilling operation was carried out with a single spindle speed and feed rate under dry, MQL, and LCO_2 conditions. After the drilling operation observe which cooling environment is the best prospect for tool wear. Figure 4.10 shows tool wear and tool pre-setting device.

Fig. 4.10: Tool pre-setting device

4.3 Experimental Plan

All the experimental work was carried out on a CNC milling machine with drilling operation under dry and wet conditions on duplex stainless steel 2205 with a TiAlN-coated solid carbide tool.

4.3.1 Experimental Investigation under dry and wet conditions

All the experimental work was carried out on a CNC milling machine with drilling operation under dry and wet conditions with TiAlN coated on DSS 2205. Minitab 20 uses a L8 orthogonal array to optimize process parameters in terms of surface roughness (Ra) using the Taguchi method.The orthogonal arrays provide a set of experiments. After the optimization of the process parameter, the Taguchi method provides a variation of the input variable to the output variable. The table is shown the characteristics of experimental work.

4.3.1.1 Cutting parameters and response variables

All the experiments are conducted with TiAlN coated solid carbide drill on duplex stainless steel 2205. In this machining process, three dependent parameters as machining environment, spindle speed, feed rate, and surface roughness as performance factors with a nominal diameter of drill 6 mm. The details of cutting parameters for machining DSS 2205 are given in table 4.7 and are based on the trial experiment and literature review based.

Table 4.7: Level of Process Parameters

S.No.	Process Parameters	Unit	Level	
1	Environment (E)	-	Dry (1)	Wet / Flood (2)
2	Spindle Speed (SS)	RPM	600	900
3	Feed Rate (FR)	mm/rev.	0.03	0.05

4.3.1.2 Design of Experiment (DOE)

The Taguchi design of the experiment was created by Genichi Taguchi, who employed an orthogonal array to optimize the statistical design procedure. Orthogonal arrays are used to develop the number of experiments, and an ANOVA is used to determine the effect of each process variable on the results. In the current investigation, the Taguchi L8 experiment design is utilized for conducting drilling experiments on DSS 2205 under dry, and wet conditions. It minimizes experimental error and improved the accuracy of the investigation. The set of the experiment is presented in table 4.8, respectively.

These are some steps of the design of experiments using the Taguchi method. Which are below;

- Identify the quality attribute that has to be improved.
- Choosing the parameters for the input and output.
- Identified the ideal concentrations of control factors.
- Plan the set of experiments and specify how the data will be analyzed.
- •The experiment is then carried out for each run.

Table 4.8: Set of Experiments

S.No.	Machining Environment (E)	Spindle speed (RPM)	Feed Rate (mm/rev.)
1	Dry (1)	600.00	00.03
2	Dry (1)	600.00	00.05
3	Dry (1)	900.00	00.03
4	Dry (1)	900.00	00.05
5	Wet (2)	600.00	00.03
6	Wet (2)	600.00	00.05
7	Wet (2)	900.00	00.03
8	Wet (2)	900.00	00.05

4.3.2 Experimental Investigation under dry, MQL, and LCO_2 Condition

All the experimental work was carried out on DSS 2205 with TiAlN coated solid carbide drill under three environmental conditions e.g. dry machining, MQL machining, and machining with LCO_2. Table 4.9 shows details of the experimental condition.

Table 4.9: Experimental condition details

Machine	VMC (Vertical milling machine)
Workpiece material and its descriptions	Duplex stainless steel 2205, 5 thickness and 300mm * 300 mm.
Cutting tool	TiAlN coated solid carbide 55 HRC.
Tool holder	SK 30 DIN69871-A
Machining conditions	Dry (without coolant), Minimum quantity of lubrication (MQL), and cryogenic (Liquid carbon dioxide LCO_2)
Flow conditions	MQL: Pressure 1.5 bar. LCO2: Pressure 35 bar, flow rate 18 l/min.
Operation and type of hole	Drilling and through-hole
Nozzle diameter	MQL: 1 mm., LCO2: 2.5 mm

4.3.2.1 Cutting parameters and response variables

All the experiments are conducted on duplex stainless steel 2205 with TiAlN coated solid carbide drill. In this machining process, three dependent parameters as machining environment, spindle speed, feed rate whole surface roughness, and hole deviation are performance factors with a nominal diameter of drill 6 mm. The details of cutting parameters for machining DSS 2205 are given in table 4.10.

Table 4.10: Level of Process Parameters

S.No.	Process Variables	Units	Level		
			1	**2**	**3**
1	Environment (E)	-	Dry (1)	MQL (2)	LCO_2(3)
2	Spindle Speed (SS)	RPM	720	920	1120
3	Feed rate (F)	mm/rev.	0.02	0.04	0.06

4.3.2.2 Design of Experiment (DOE)

The Taguchi design of the experiment was created by Genichi Taguchi, who employed an orthogonal array to optimize the statistical design procedure. Orthogonal arrays are used to develop the number of experiments, and an ANOVA is used to determine the effect of each process variable on the results. In the current investigation, the Taguchi L9 experiment design is utilized for conducting drilling experiments on DSS 2205 under dry, MQL, and LCO_2 conditions. It minimizes experimental error and improved the accuracy of the investigation. The set of the experiment is presented in table 4.11, respectively.

Table 4.11: Set of experiments under dry, MQL, and LCO_2 conditions

Exp. No.	Input Parameters		
	Environment (E)	**Spindle Speed (SS)**	**Feed rate (F)**
1	1	720	0.02
2	1	720	0.04
3	1	720	0.06
4	2	920	0.04
5	2	920	0.06
6	2	920	0.02
7	3	1120	0.06
8	3	1120	0.02
9	3	1120	0.04

4.3.3 Experimental Investigation under hybrid MQL-LCO_2 condition

The minimum quantity of lubrication (MQL) and cryogenic with liquid carbon dioxide (LCO2) were constructed on a CNC milling machine for the experiments. Figure 22 is an actual picture of a CNC milling machine setup for hybrid machining (MQL+LCO_2). An MQL setup consists of a compressed inlet valve, flow meter, regulating valve, pipe (1 mm), mixer nozzle (air + vegetable oil), and a cryogenic setup consists LCO_2 cylinder (35 bar pressure), flow meter, regulating valve, hose pipe (2 mm) and nozzle (1mm). In this chapter, the MQL+LCO2 flows together in the machining zone and improves tool wear and surface quality by reducing cutting temperature. Table 4.12 shows the characteristics the of MQL+LCO_2 setup.

Table 4.12: Shows the Characteristics of the MQL+LCO_2 Setup

Description	Specification
Machine	CNC milling
Process	Drilling
Workpiece material	DSS 2205
Tool Material	TiAlN-coated solid carbide
Oil type	Vegetable oil
The pressure of MQL Flow	3 Bar
The pressure of the LCO2 cylinder	35 Bar
The flow rate of LCO2	18 l/m
Response measured	CMM

The 300 mm * 300 mm, 5 mm thick flat plate of duplex stainless steel 2205 was used for all of the studies. Following optical emission scanning (OES), the composition of duplex stainless steel 2205 was discovered and is displayed in Table 4.13.

Table 4.13: Chemical Composition of DSS 2205

Element	Carbon	Chromium	Nickel	Molybdenum	Nitrogen	Others
%	0.030%	21-23%	5.5-6.5 %	3.1-35%	0.18-0.20%	S-0.001-0.020% P-0.030%, Si-1%

In this study, drill diameter, spindle speed, and feed rate were selected as input parameters and hole deviation, cylindricity error, and circularity error were selected as output responses. The effective range of each parameter was selected after doing trial experiments. Table 4.14 shows the level of process parameters with their range.

Hybrid MQL-LCO$_2$ Technique

Environmental concerns are now real in the machining sector. As a result, a novel cooling-lubrication system that fuses MQL and CO_2 cryogenic technologies is presented in this research. This novel cooling-lubrication system seeks to provide a more environmentally and economically responsible option. Figure 4.11 shows the hybrid machining setup.

4.3.3.1 Cutting parameters and response variables

In the present study, three levels of three input factors have been selected by using the Box-Behnken design of response surface method (RSM), which generates 15 sets of experiments. The experimental matrix and experimental value are shown in table 3.12. To measure hole deviation, cylindricity error, and circularity error, a CMM machine is used.

The details of cutting parameters for machining DSS 2205 are given in table 4.14.

Table 4.14: Level of process parameters

Input Factor			Coded Level		
Description	**Units**	**Symbol**	**-1**	**0**	**1**
Drill Diameter	mm	DD	2	4	6
Spindle Speed	RPM	SS	1100	1300	1500
Feed Rate	mm/rev.	F	0.01750	0.01875	0.020

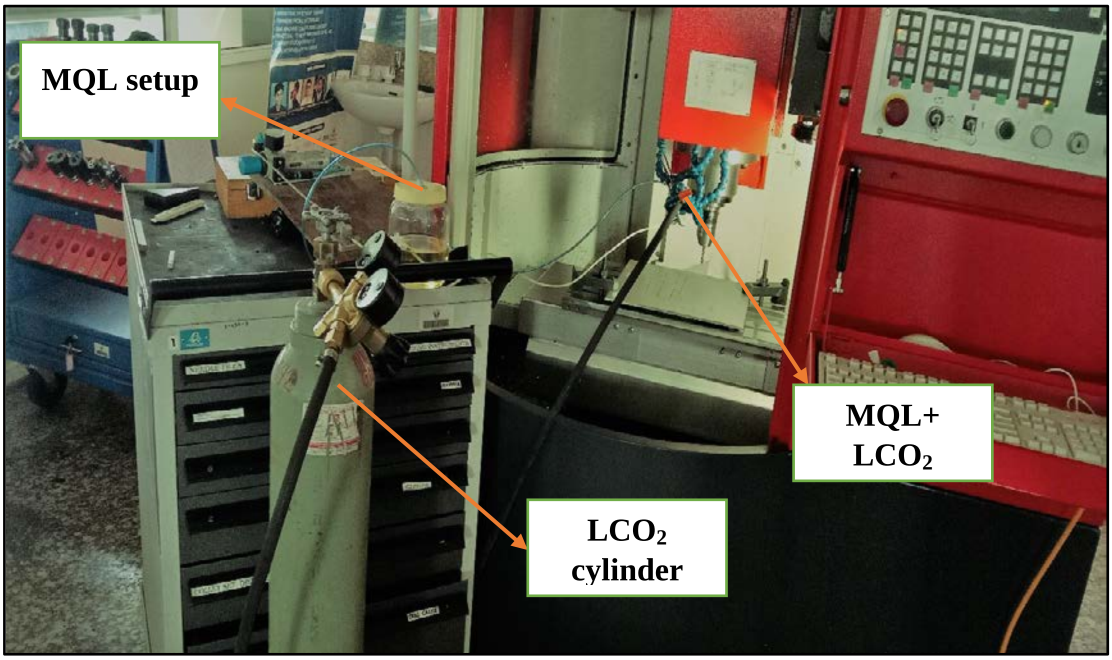

Fig. 4.11: Hybrid MQL-LCO$_2$ setup

4.3.3.2 Design of experiment

The design of the experiment used the Box-Behnken design of response surface method (RSM), which used an orthogonal array to optimize the statistical design process. The Taguchi technique analyses variance (ANOVA). The number of experiments is developed by using orthogonal arrays, and ANOVA calculates the contribution of each process variable to the outcomes. In the current investigation, a total of 15 sets of experiment design is utilized for conducting drilling experiments on DSS 2205 under hybrid MQL-LCO$_2$condition. It minimizes experimental error and improved the accuracy of the investigation. The set of the experiment is presented in table 4.15, respectively.

Table 4.15: Set of experiments under the hybrid cooling condition

Run order	Drill Diameter	Spindle Speed	Feed Rate	Experimental Value		
				Hole Deviation	Cylindricity	Circularity
1	-1	0	1	0.02920	0.03560	0.00610
2	0	-1	1	0.0305805	0.02840	0.00630
3	1	1	0	0.0236500	0.03200	0.00540
4	0	0	0	0.027350	0.03360	0.00560
5	-1	0	-1	0.027600	0.03100	0.00550
6	1	0	-1	0.025040	0.02950	0.00544
7	-1	-1	0	0.028200	0.02760	0.00567
8	0	0	0	0.027100	0.02870	0.00550
9	1	-1	0	0.027700	0.02300	0.00575
10	0	1	-1	0.025400	0.03060	0.00530
11	0	1	1	0.02700	0.03510	0.00589
12	1	0	1	0.028820	0.03120	0.00561
13	0	-1	-1	0.02900	0.02170	0.00602
14	-1	1	0	0.027900	0.04080	0.00597
15	0	0	0	0.028100	0.03259	0.00552

4.4 Measured Responses

4.4.1 Surface Roughness (Ra)

Surface finish includes surface roughness, also known as roughness (surface texture). It is measured by how far an actual surface deviates from its ideal form in the direction of the normal vector. The surface is characterized as rough if these variations are considerable and smooth if they are minimal. Roughness is frequently regarded in surface metrology as the high-frequency, short-wavelength component of a measured surface. In order to make sure that a surface is suitable for a purpose, it is frequently required in practice to know both the amplitude and frequency.

In tribology, rough surfaces often have greater friction coefficients and wear more quickly than smooth surfaces. Since surface irregularities may serve as initiation locations for cracks or corrosion, roughness is frequently a reliable indicator of how well a mechanical component will operate. Roughness, on the other hand, might encourage adherence. In general, cross-scale descriptors like surface fractality offer more accurate predictions of mechanical interactions at surfaces, such as contact stiffness and static friction, than scale-specific descriptors. The fundamental mechanism of surface roughness is shown in Figure 4.12.

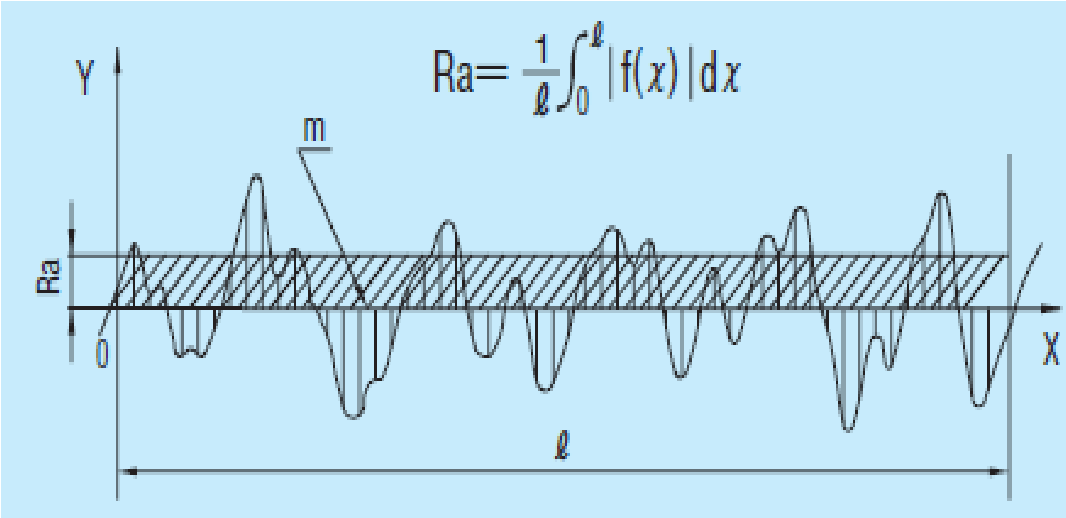

Fig. 4.12: Shows surface roughness (He et al., 2021)

4.4.2 Hole deviation

Hole deviation is the drill bit's unintended departure from a chosen borehole trajectory. The tendency of the bit to veer off the intended route when drilling a straight or curved hole section can result in drilling issues like greater drilling costs and legal issues with lease boundaries. Hole deviation examples are shown in Figure 4.13.

Cause of hole deviation

What specifically causes a drill bit to stray from its planned course is unknown. However, it is commonly acknowledged that one or a combination of the following elements may be to blame for the deviation:

- Drill string characteristics, specifically the bottom hole assembly makeup.
- Stabilizers (location, number, and clearances).
- Applied weight on the drill bit.
- The vertical angle of the hole -an inclination

- Drill-bit type and its basic mechanical design
- Hydraulics at the bit
- Improper hole cleaning

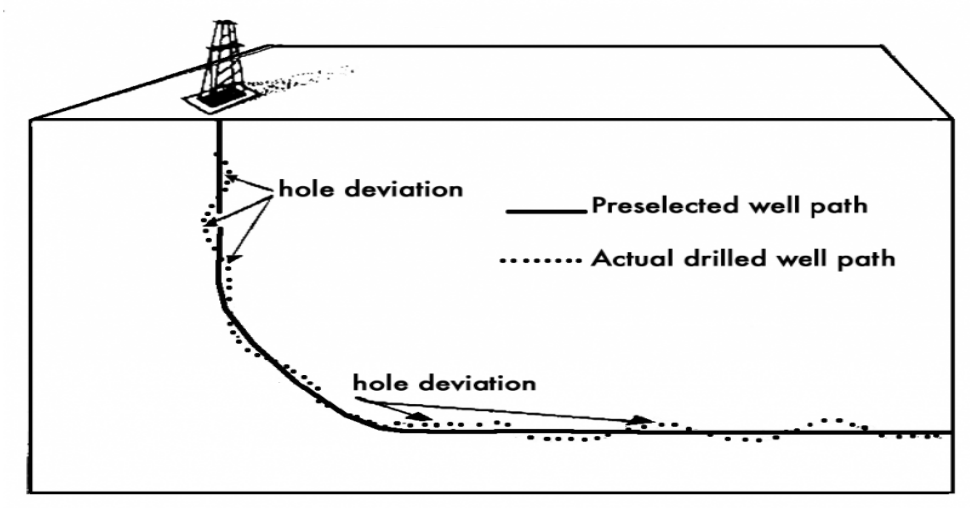

Fig. 4.13: Shows the principle of hole deviation (Amiri, 2017)

4.4.3 Cylindricity Error

A thorough index for regulating the roundness, straightness, and parallelism of a cylinder's longitudinal and transverse sections as well as its axis is the cylindricity error. The radius difference between two coaxial cylinders with the real surface having the least radius is referred to as cylindrical tolerance.

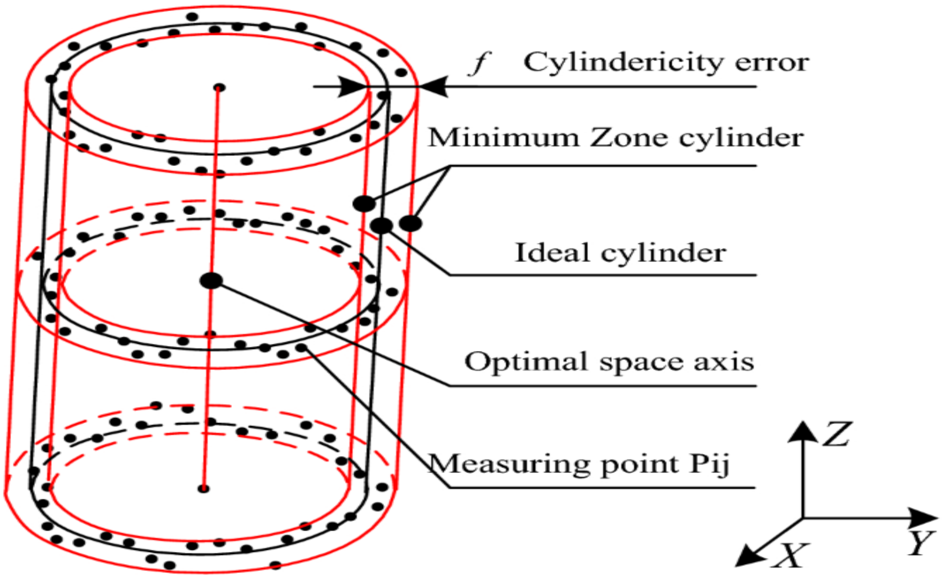

Fig. 4.14: Basic concept of cylindricity error [Wang et al., 2022]

4.4.4 Circularity Error

Circularity error are defined by the diameter difference between the largest circle that can be drawn inside the section (also known as an inscribed circle) and the smallest circle that can be drawn outside the section (also known as a circumscribed circle) while maintaining concentricity between the two circles is the circularity error for a given circular section. There is no division necessary because it is a diameter measurement.

Circularity Error = Largest circle size – Smallest circle size

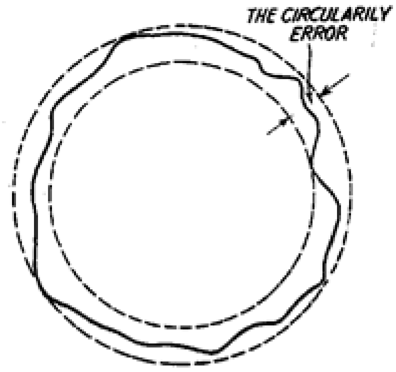

Fig. 4.15: Basic concept of circularity error [Gaitonde et al., 2014]