INVESTIGATION ON TOOL LIFE AND HOLE QUALITY OF INCONEL 718 IN DRILLING OPERATION USING LN_2 AS COOLANT

A PROJECT REPORT

submitted by

SOHAIL KHAN S

Reg. No: TKM21MEIR10

to

the APJ Abdul Kalam Technological University
in partial fulfilment of the requirements for the award of the Degree
of
Master of Technology

in

Mechanical Engineering

Specialization*: Industrial Refrigeration and Cryogenic Engineering*

Department of Mechanical Engineering

THANGAL KUNJU MUSALIAR COLLEGE OF ENGINEERING

KOLLAM

MAY 2023

DEPARTMENT OF MECHANICAL ENGINEERING
TKM COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

This is to certify that the report entitled **"INVESTIGATION ON TOOL LIFE AND HOLE QUALITY OF INCONEL 718 IN DRILLING OPERATION USING LN_2 AS COOLANT"** submitted by **SOHAIL KHAN S, Reg No: TKM21MEIR10** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Industrial Refrigeration and Cryogenic Engineering is a bonafide record of the project work carried out by him under my guidance and supervision. This report in any form has not beensubmitted to any other University or Institute for any purpose.

Internal Supervisor:

Dr. Anand Sekhar R
Assistant professor
Department of Mechanical Engineering
TKM College of Engineering , Kollam-5

PG Coordinator:

Dr. Shafi K A
Professor
Department of Mechanical Engineering
TKM College of Engineering , Kollam-5

Head of the Department:

Dr. Dileep P N
Professor
Department of Mechanical Engineering
TKM College of Engineering , Kollam-5

DECLARATION

I **Sohail Khan S**, hereby declare that the project report "Investigation on tool life and hole quality of Inconel 718 in drilling operation using LN_2 as coolant", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of **Dr.Anand Sekhar R.** This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma, or similar title of any other University.

Sohail Khan S Sohail
Register No: **TKM21MEIR10** of year **2021-23**
May 2023

Internal Supervisor:

Dr. Anand Sekhar R
Assistant Professor
Department of Mechanical Engineering
TKM College of Engineering , Kollam-5

Head of the Department:

Dr. Dileep P N
Professor
Department of Mechanical Engineering
TKM College of Engineering , Kollam-5

ACKNOWLEDGEMENT

Any attempt at any level cannot be satisfactorily completed without the support and guidance of learned people. I owe to great many people whose constant support and motivation that has encouraged me to come up with this project.

Firstly, I would like to express my heartfelt thanks to **Dr. Anand Sekhar R**, Assistant Professor, Department of Mechanical Engineering, TKM College of Engineering for being instrumental in the completion of my project with his guidance.

I would like to thank **Dr. Dileep P N**, Professor and Head of the Department, Department of Mechanical Engineering, TKM College of Engineering for the support to complete this project. I thank **Dr. Shafi K A**, PG Coordinator, Department of Mechanical Engineering, TKM College of Engineering for giving their constant support for doing this project.

I express my deep sense of gratitude to **Johnson Y.,** workshop instructor and **Nazeer Khan A.**, trades man, Refrigeration and Air conditioning lab, **Sharafudeen S**, Trade instructor, **Yohannan Kutty D**, Trade instructor and **Jayakumar K**, Workshop Superintendent, Mechanical Engineering Workshop for their constant help and assistance for the project. I also thank other college staffs for the technical and nontechnical assistance given for the project. Finally, I take this opportunity to extend my deep appreciation to family and friends, for all that they meant to me during the crucial times of the completion of this project.

SOHAIL KHAN S
MAY 2023

ABSTRACT

The main focus of the research was to investigate the process of machining Inconel 718 alloy using a Tungsten Carbide tool with a diameter of 6mm. Inconel 718 is a challenging material to machine due to its hardness and low thermal conductivity. The research aimed to enhance the quality of the hole surface while drilling Inconel 718. To achieve this, experiments were conducted using a Carbide tool under different cutting speeds, with both dry and cryogenic cooling conditions. The quality of the hole surface was then evaluated using SEM images and compared between the two conditions. The cutting speeds used in the experiments were 700rpm, 900rpm, and 1100rpm.The results of the experiments revealed that drilling Inconel 718 under dry conditions produced poor surface quality due to the generation of heat during the process. On the other hand, drilling under cryogenic conditions resulted in better hole surface quality. Additionally, the thrust force during drilling was greater under cryogenic conditions compared to dry conditions. These findings suggest that cryogenic cooling can be a useful method for enhancing the hole surface quality when drilling Inconel 718, and this method can be applied in industrial settings to improve the efficiency of the machining process.

Keywords: Cryogenic coolant, Inconel 718, Carbide Tool, Drilling operation, Liquid Nitrogen, Hole quality

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Inconel 718 is a high-strength, corrosion-resistant nickel-based alloy and is used in a wide range of applications, including aerospace, gas turbines, and nuclear reactors. Inconel 718 has excellent mechanical properties at both low and high temperatures, making it ideal for use in extreme environments. It has a high tensile strength and can maintain its properties at temperatures up to 1300°F (704°C). One of the key advantages of Inconel 718 is its resistance to corrosion and oxidation, even at high temperatures. This makes it a popular choice for use in harsh environments, such as in the aerospace industry where it is used in engine components and structural parts.[1] Inconel 718 is also highly resistant to fatigue and creep, making it an ideal material for use in gas turbine engines, where it is used in components such as blades, discs, and casings. Overall, Inconel 718 is a highly versatile and reliable material that is widely used in a variety of industries and applications where high strength, corrosion resistance, and reliability are required.

Inconel 718 is a nickel-based superalloy that is composed of several elements in varying proportions. The exact composition can vary depending on the manufacturer, but typically it includes:

Table 1.1. Inconel 718 Chemical composition

Alloy	Composition(%)
Nickel (Ni)	50-55%
Chromium (Cr)	17-21%
Iron (Fe)	balance (remainder after other elements are added)
Niobium (Nb)	4.75-5.5%
Molybdenum (Mo)	2.8-3.3%
Titanium (Ti)	0.65-1.15%
Aluminum (Al)	0.2-0.8%
Cobalt (Co)	1%
Copper (Cu)	0.3%
Carbon (C)	0.08%
Manganese (Mn)	0.35%
Silicon (Si)	0.35%

In addition to these elements, Inconel 718 may also contain trace amounts of other elements such as sulphur, phosphorus, and boron. The specific composition of Inconel 718 is designed to provide a combination of high-temperature strength, good corrosion resistance, and good weldability, making it well-suited for use in a variety of demanding applications.

Inconel 718 has a number of desirable properties that make it a popular choice for high-stress, high-temperature applications. Here are some of its key properties:

- *High strength*: Excellent strength at both high and low temperatures, making it suitable for use in demanding applications where strength is critical.
- *Good corrosion resistance*: Highly resistant to corrosion and oxidation, making it suitable for use in harsh environments where other materials would quickly degrade.[2]
- *Good fatigue resistance*: Good resistance to fatigue and stress corrosion cracking, allowing it to withstand cyclic loading and stress fluctuations over long periods of time.
- *Excellent weldability*: Can be welded using a variety of techniques, making it easy to work with and suitable for a wide range of applications.
- *High temperature resistance*: Retains its strength and other properties at high temperatures up to around 1300°C (2372°F), making it suitable for use in high-temperature applications such as gas turbines, jet engines, and nuclear reactors.
- *Good machinability*: Relatively easy to machine, making it suitable for use in a wide range of applications where complex shapes and tight tolerances are required.
- Physical and Thermal properties of Inconel 718 are listed in table 1.2. and 1.3. respectively.

Table 1.2. Physical Properties of Inconel 718

Density	8.19 g/cm^3
Melting point	1280-1343°C
Thermal conductivity	6.7 W/m-K
Specific heat capacity	427 J/kg-K
Electrical resistivity	$1.27 \times 10^{-6}\Omega m$

Table 1.3. Thermal Properties of Inconel 718

Coefficient of thermal expansion	13.9 µm/m-K (at 20°C)
Thermal conductivity	6.7 W/m-K
Maximum service temperature:	704°C
Thermal stability	Inconel 718 has good thermal stability, meaning it retains its properties at high temperatures and in high-stress environments
Thermal shock resistance	Inconel 718 has good thermal shock resistance, meaning it can withstand sudden changes in temperature without cracking or breaking.

1.1 Machinability of Inconel 718

Inconel 718 is a challenging material to machine due to its high strength and resistance to heat and wear. However, with the right tools and techniques, it can be machined successfully.[3] Here are some of the factors that affect the machinability of Inconel 718:

- *Hardness*: Relatively hard material, which can make it difficult to machine. It has a typical hardness of around 35 HRC (Rockwell C scale).
- *Heat resistance*: Has excellent heat resistance, which means that it can quickly transfer heat to cutting tools and cause them to wear out more quickly.
- *Toughness*: Tough material that can be challenging to cut without causing excessive tool wear or chipping.[4]
- *Work hardening*: Tends to work harden during machining, which can cause it to become even harder and more difficult to machine.

To machine Inconel 718 successfully, special tools and techniques are required. Cutting tools made from carbide or ceramic materials are often used, as they are more resistant to wear and heat.[5] Cutting speeds should be kept low to avoid overheating, and plenty of coolant should be used to dissipate heat and prevent tool wear.[6] In addition, frequent tool changes may be necessary to maintain the quality of the cut.

Overall, while Inconel 718 is a challenging material to machine, with the right approach it can be machined successfully to produce high-quality parts.

Drilling Inconel 718 can be challenging due to its unique combination of high strength, high hardness, and high-temperature resistance. Here are some common drilling problems that can occur when drilling Inconel 718:

- *Tool wear*: It is a tough material that can wear down a standard drill bit quickly. Tool wear can lead to a loss of accuracy, surface finish quality, and increased drilling time.[7]
- *Work hardening*: It can work harden during drilling, making it more difficult to drill as the drilling process progresses.
- *Overheating*: It generates a lot of heat during drilling due to its high-temperature resistance. Overheating can cause the workpiece to warp, the drill bit to dull, and can lead to inaccuracies in the hole.
- *Chip control*: It produces long and stringy chips that can wrap around the drill bit and cause it to break or bend. Chip control is essential when drilling Inconel 718.
- *Drill wander*: It is a tough material that can cause the drill bit to wander or skip during drilling, leading to inaccuracies in the hole.

  To overcome these problems, it is important to use the appropriate drilling techniques and equipment, as well as the appropriate tooling and cutting fluids.[8] Properly trained and experienced personnel should perform drilling operations on Inconel 718 to ensure a successful outcome.

Dry drilling of Inconel 718, which means drilling without any coolant or lubricant, can be challenging due to the high strength, hardness, and temperature resistance of the material. However, it is possible under certain conditions i.e., use of a high-speed steel or carbide drill bit with a sharp point and a high helix angle to reduce cutting forces and prevent work hardening, use a drill bit with a TiN, TiCN, or TiAlN coating,[9] which can help reduce heat buildup and extend the life of the drill bit, use a low cutting speed to minimize heat buildup. The recommended cutting speed for dry drilling of Inconel 718 is between 40 and 60 surface feet per minute (SFM), use a high clamping force to prevent movement or vibration during drilling, which can cause damage or inaccuracies in the hole.

One alternative method that has been used to overcome this challenge is to use liquid nitrogen as a coolant during the drilling process.[10] Liquid nitrogen can be used as a coolant because of its extremely low temperature (-320°F), which can help reduce the temperature at the cutting edge and the workpiece, thereby prolonging the life of the drill bit and preventing damage to the workpiece.[11] The use of liquid nitrogen as a coolant requires specialized equipment, such as a cryogenic cooling system, to deliver and control the flow of the coolant to the cutting zone.[12] Liquid nitrogen can cause the workpiece to become brittle and prone to cracking, so it is important to use appropriate clamping and fixturing techniques to minimize vibration and stress during the drilling process.se of liquid nitrogen can reduce the need for chip evacuation because it can freeze the chips and help prevent them from clogging the hole.[13] The use of liquid nitrogen can also reduce the need for post-processing operations because it can minimize the heat-affected zone and the formation of burrs.

1.2 RESEARCH GAP

Drilling of Inconel 718 is a challenging process due to the material's high strength, high-temperature resistance, and work hardening tendency. Although considerable research has been conducted on the drilling of Inconel 718, there are still some research gaps that need to be addressed. Some of the research gaps include:

1. Development of new cutting tools and coatings specifically designed for Inconel 718 drilling to improve tool life, surface finish, and productivity.[14]
2. Investigation of the effects of cutting parameters, such as cutting speed, feed rate, and depth of cut, on drilling performance, tool wear, and surface quality.
3. Exploration of new cooling and lubrication techniques, such as cryogenic cooling, minimum quantity lubrication, and high-pressure coolant, to improve drilling performance and reduce the environmental impact of coolant use.[15]
4. Characterization of the microstructure and mechanical properties of the drilled hole, including the formation of burrs, work hardening, residual stresses, and surface integrity.[16,17]
5. Investigation of the influence of drilling on the fatigue life and damage tolerance of Inconel 718 components, especially for aerospace and defense applications.
6. Optimization of the drilling process for different Inconel 718 alloys, which can have varying compositions, microstructures, and mechanical properties.
7. Development of predictive models and simulation tools to predict drilling performance and optimize the drilling process.[18]

Overall, the drilling of Inconel 718 is a complex process that requires further research to improve the efficiency, quality, and safety of the process. Addressing the research gaps outlined above can help achieve these goals and facilitate the wider adoption of Inconel 718 in various industries.

1.3 OBJECTIVES

- To drill the Inconel 718 alloy plate under dry condition.
- To drill the Inconel 718 alloy plate using LN_2 as coolant condition.
- To study the drilling force requirement in dry condition and using LN_2 as coolant.
- To study the hole surface quality under the two test conditions.

1.4 METHODOLOGY

Workpiece and tool preparation: The workpiece, Inconel 718, is first prepared for drilling. The cutting tool, which is selected based on the drilling operation requirements and material properties, is also prepared. The liquid nitrogen cooling system is set up and the cooling nozzles are positioned to provide the necessary cooling to the cutting zone. The drilling parameters such as spindle speed, feed rate is optimized to achieve the desired hole quality and tool life while using liquid nitrogen coolant. The drilling operation is carried out by directing the flow of liquid nitrogen onto the cutting zone using the cooling nozzles. The cooling provided by the liquid nitrogen reduces the temperature of the cutting zone, thereby reducing the heat generated during the drilling operation.[19] During the drilling operation, the drilling parameters such as spindle speed, feed rate are continuously monitored to ensure that they remain within the optimal range. The Force analysis and hole surface quality is done. The Flowchart for the methodology is shown in figure 1.1.

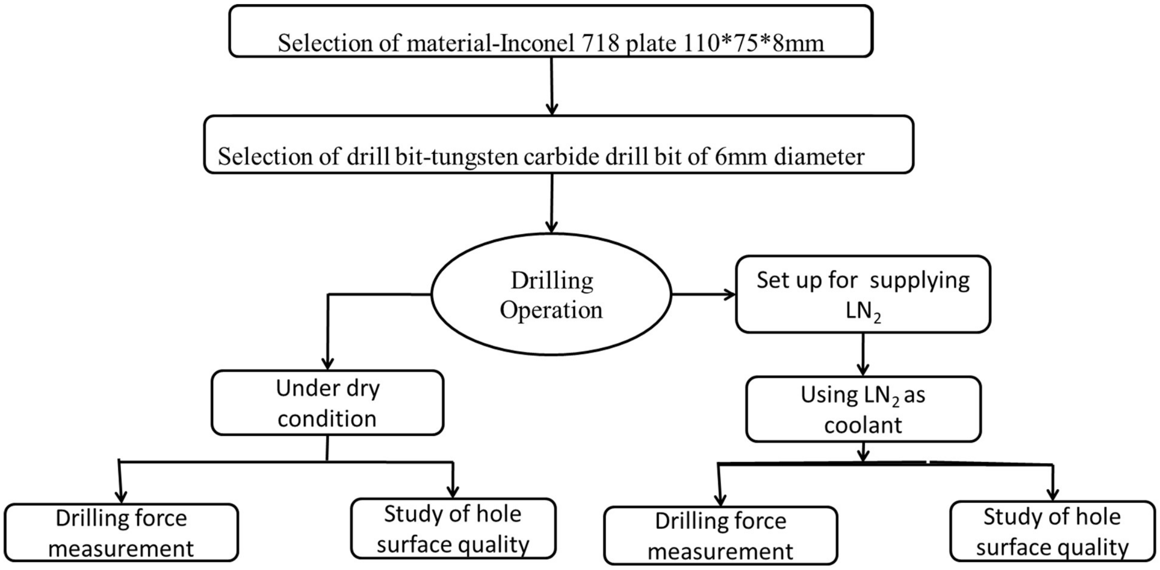


Fig 1.1 Flowchart of Methodology

CHAPTER 2
LITERATURE REVIEW

The use of liquid nitrogen (LN2) as a coolant in the drilling of Inconel 718 has gained significant attention in recent years due to its potential to improve tool life and hole quality. Several studies have investigated the effects of LN2 cooling on Inconel 718 drilling, including the investigation on tool life and hole quality. Here is a brief literature review of some of these studies:

In a study by Shokrani, found that liquid nitrogen coolant was effective in reducing surface roughness, particularly at higher cutting speeds and feed rates. However, the study also highlighted the importance of optimizing the cutting parameters and tool geometry for achieving optimal outcomes when using liquid nitrogen coolant.[20]

In a study by A.H.Musfirah, while machining Inconel 718 alloy, the use of cryogenic cooling was found to result in a significantly better surface roughness compared to dry milling.Cryogenic cooling proved to be more effective in improving the integrity of the machined surface compared to dry milling.[21]

In a study by NecatiUsak, shows a significant reduction in cutting temperature by spraying LN2 is provided and improves the hole quality in terms of lower burr formation. Cutting temperature measurements and performance evaluation tests confirm that in dry conditions led to high temperatures in cutting zone, high torque values due to BUE.[22]

In a study by S. Chaabani, results indicated that all of the cryogenic coolants tested, including liquid nitrogen, liquid carbon dioxide, and liquid argon, were effective in reducing tool wear and also found that the use of cryogenic cooling led to a decrease in cutting temperature, which is an important factor in prolonging tool life and improving machinability.[23]

In a study by Navneet Khanna, found that tool life can be significantly increased by 87.5% when drilling Inconel 718 alloy under cryogenic conditions, compared to dry drilling. Additionally, the torque required to drill a hole was found to decrease up to 30% under cryogenic drilling compared to dry drilling.[24]

In a study by M. Gueli, found that the use of flood coolant significantly reduced tool wear and cutting forces They also observed that the optimal cutting parameters for flood coolant slot milling of Inconel 718 were different from those for dry milling.[25]

In a study by Ivan Sunit Rout, showed that using a cryogenically treated ceramic tool for machining Inconel 718 alloy, in combination with the cutting fluid KoolKut 40, resulted in better performance. Cryogenically treated ceramic tools have been treated with liquid nitrogen to improve their wear resistance.[26]

In a study by Andrea De Bartolomeis, highlighted the need for interdisciplinary research that combines machining science, materials science, and computer modeling to gain deeper understanding of the complex phenomena involved in the machining of Inconel 718. [27]

In a study by EminSalur, suggests that the combination of cryogenic cooling and slower cutting speeds and feed rates can be a more effective and efficient approach to machining. By minimizing tool wear, this approach can improve the lifespan of the cutting tool and potentially lead to better overall machining outcomes.[28]

In a study by Prassan Shah, found that both coolants resulted in improved machining performance in terms of reduced tool wear and better hole quality compared to dry drilling.LN_2 was found to be more effective in reducing tool wear and achieving better hole quality than LCO_2.[29]

2.1SUMMARY OF THE LITERATURE REVIEW

The literature review suggests that drilling Inconel 718 is a challenging process due to its high strength, toughness, and work hardening tendency. However, the use of appropriate cutting parameters and cooling strategies,[30] as well as the use of advanced cutting tool coatings, can significantly improve tool life and hole quality during drilling. Studies have shown that factors such as cutting speed, feed rate, drill point angle, and cooling strategy (such as cryogenic cooling using liquid nitrogen) can affect tool wear and hole quality. The use of cryogenic coolants on drilling tools has shown to improve tool life and hole quality in drilling Inconel 718.[31] Overall, the literature suggests that further research is needed to develop more effective drilling strategies for Inconel 718, particularly in the areas of reducing burr formation and improving hole quality.

CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3.1RADIAL DRILLING MACHINE

The MAS VR2 radial drilling machine has a maximum drilling capacity of 50 mm and can handle workpieces weighing up to 2,500 kg. The machine has a vertical column with a diameter of 360 mm and an arm that can move up and down the column, as well as rotate around it. The drill head of the MAS VR2 radial drilling machine can rotate at speeds ranging from 300 to 3600 rpm and can be adjusted for different feed rates. The machine has a coolant system that can be used to keep the drill bit cool and lubricated during operation, which helps to prolong the life of the drill bit and improve drilling accuracy. The MAS VR2 radial drilling machine is designed with safety features, including a safety clutch that protects the machine and operator from overloading. Overall, the MAS VR2 radial drilling machine is a reliable and versatile tool that is ideal for heavy-duty drilling operations in industrial manufacturing and construction applications. MAS VR2 is shown in figure 3.1.

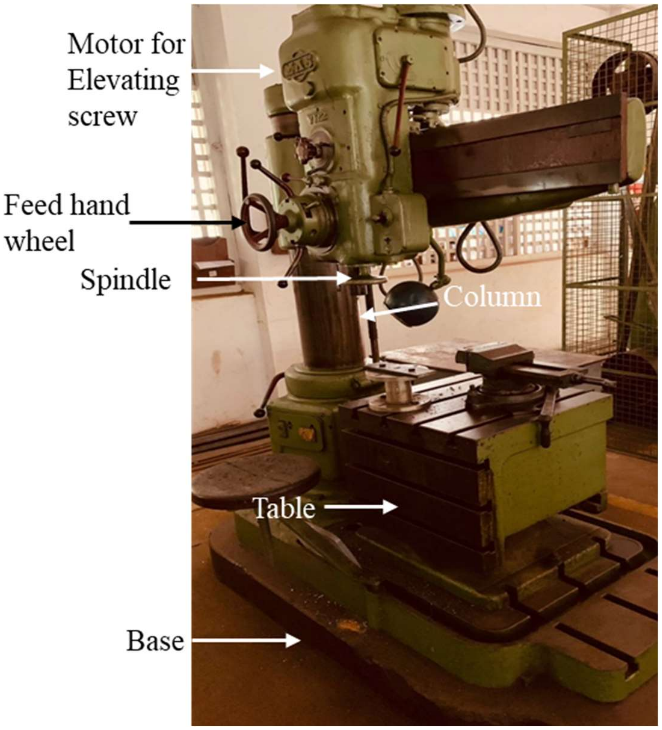


Fig 3.1. Radial drilling machine

3.2 DYNAMOMETER

A dynamometer for drilling is a tool used to measure the force and torque exerted on a drill bit during drilling operations. It is typically installed between the drilling machine and the drill bit and can be mechanical or electronic in nature. A mechanical dynamometer for drilling works by using a spring or a strain gauge to measure the force exerted on the drill bit. As the bit moves through the material being drilled, it produces a force that compresses the spring or strain gauge, and this compression is then translated into a reading on a dial or gauge. An electronic dynamometer for drilling uses sensors and transducers to convert the force and torque into an electrical signal, which is then displayed on a digital readout. The electronic dynamometer can also provide real-time data on the drilling operation, allowing operators to monitor and adjust the drilling process for optimal performance and efficiency. The dynamometer for drilling provides crucial information to the operator, such as the feed force, cutting force, and torque. This information can be used to optimize the drilling process by determining the appropriate cutting speeds, feed rates, and tool geometry. It can also help to detect problems such as tool wear or breakage, allowing for corrective action to be taken before damage occurs. The drill tool dynamometer is shown in fig 3.2.

Fig 3.2. Drill Tool Dynamometer

3.3MATERIAL SELECTION

Inconel 718 plate is typically available in a range of thicknesses and sizes, and can be purchased from various suppliers and distributors around the world. The plate is often fabricated through a process known as hot rolling, which involves heating the material to a high temperature and then rolling it into a flat sheet. When selecting an Inconel 718 plate, it is important to consider factors such as the required thickness, size, and surface finish, as well as the specific application and environmental conditions in which it will be used.[32]

Here we have selected Inconel 718 plate of length 110mm, width 75mm and of thickness 8mm is selected for drilling. Since this is a hard material proper cutting tool must be used. As a result, special cutting tools are often required to machine Inconel 718 effectively and efficiently. One of the most common types of cutting tools used for Inconel 718 is carbide inserts. Carbide inserts are made from a combination of tungsten carbide and cobalt and are designed to withstand high temperatures and maintain their sharpness over time.

Fig. 3.3. Inconel plate of dimension 110mm*75mm*8mm

3.4 CUTTING TOOL

A tungsten carbide drill bit is a type of cutting tool used for drilling holes in a variety of materials, including metal, wood, plastics, and composites. Tungsten carbide drill bits are made from a composite material of tungsten carbide particles and a metallic binder, usually cobalt or nickel. Tungsten carbide is a very hard and wear-resistant material that is ideal for cutting tools. It is composed of tungsten and carbon atoms and has a high melting point and high hardness, making it suitable for use in high-speed drilling operations. The metallic binder in tungsten carbide drill bits serves to hold the tungsten carbide particles together and provide toughness and ductility to the drill bit. The composition of tungsten carbide drill bits can vary depending on the specific application and desired properties, but generally, they contain around 90-94% tungsten carbide and 6-10% metallic binder. Tungsten carbide drill bits come in a range of shapes and sizes to accommodate different drilling applications. They can be used in drilling operations that require high precision and accuracy, as well as those that require high-speed drilling of tough materials such as stainless steel and titanium.[33]

Fig. 3.4. Tungsten Carbide drill bit of 6mm diameter

3.5 DRILLING OF ALLOY PLATE

Drilling alloy plates requires careful consideration of the specific alloy being drilled and the appropriate drilling parameters to use. It is important to choose the right drill bit, use the appropriate cutting fluid, adjust the drilling speed and feed rate, and wear proper safety equipment.

On drilling Inconel 718 alloy plate Tungsten carbide drill bit of size 6mm diameter is used. Drilling of alloy was done under two conditions. Drilling without using coolant that is dry drilling and then with Liquid Nitrogen assisted drilling. A dynamometer was connected to obtain the thrust force value during drilling process. Drilling was done under different rpms of selected ranges 700,900 and 1100 rpm. On these selected rpms both dry and LN_2 assisted drilling was done and the drilling force measurement values were taken and recorded. These values were plotted against time with same feed rate for measuring and comparing Drilling force versus Time graph for different rpms of drilling. These graphs were compared to study the force analysis on Inconel 718 plate during drilling. The drilling process is shown in figure 3.5.

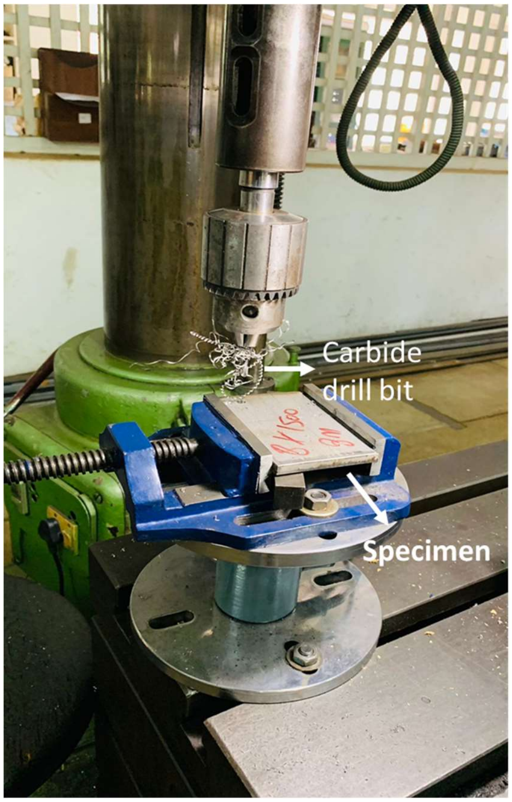


Fig 3.5. Drilling of Inconel 718 plate

3.6 LIQUID NITROGEN AS COOLANT

Liquid nitrogen is sometimes used as a coolant in drilling operations, particularly in situations where water-based fluids are not effective or desirable. Liquid nitrogen has a number of advantages as a coolant, including its ability to quickly lower temperatures and its inertness, which means it won't react with the materials being drilled. One of the main benefits of using liquid nitrogen as a coolant is its extremely low temperature (-196°C). This allows it to rapidly cool down the drill bit and other components, reducing friction and preventing overheating. This can help to prolong the life of the drilling equipment and increase drilling efficiency.[34]

However, there are also some potential drawbacks to using liquid nitrogen as a coolant. One of the main concerns is the risk of nitrogen gas being released into the air during the drilling process. Nitrogen gas is odorless and colorless, and in high concentrations, it can displace oxygen and pose a risk to workers. Proper safety precautions, such as adequate ventilation and gas detection systems, are necessary to mitigate this risk.[35]

Liquid Nitrogen was supplied using a 2mm nozzle of copper in between the drill bit and the Inconel 718 plate during drilling. Proper insulation was given to the radial drilling machine for providing safety to the parts of the equipment from spilling of Liquid Nitrogen. The schematic for LN_2 supply is shown in figure 3.6.

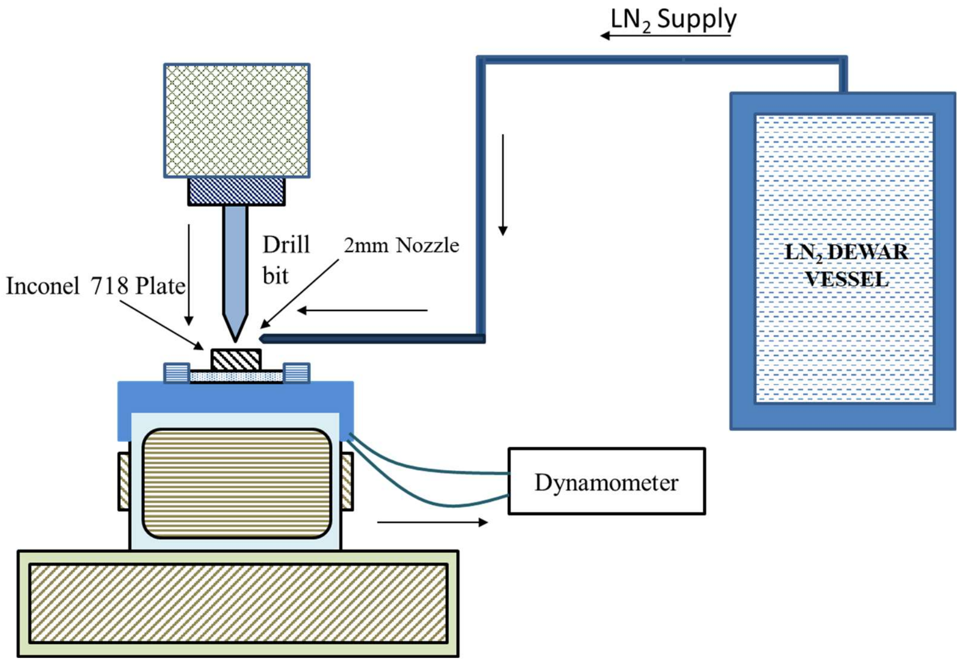


Fig 3.6. Schematic of Experimental setup

3.7 EDM WIRE CUTTING

EDM (Electrical Discharge Machining) wire cutting is a significant manufacturing process with several applications across various industries. Precision manufacturing: EDM wire cutting is a highly precise process that can produce complex shapes and intricate details with very tight tolerances. This makes it ideal for manufacturing components for industries like aerospace, medical, and automotive, where precision is critical. Unlike traditional cutting methods, EDM wire cutting does not involve physical contact between the cutting tool and the workpiece, meaning there is no tool wear or breakage. This makes it an ideal process for manufacturing parts with high accuracy and consistency. EDM wire cutting can produce complex shapes and intricate details that are difficult to achieve using traditional machining methods. This makes it a popular choice for manufacturing intricate parts like medical implants and aerospace components. EDM wire cutting produces high-quality finishes, with no burrs or rough edges. This makes it suitable for manufacturing parts that require a high-quality finish, such as medical implants and aerospace components.

Thus, EDM wire cutting is used for cutting Inconel 718 plate drilled hole for further surface studies and investigation of hole quality. EDM wire cutting process and cut pieces are shown in figure 3.7. and 3.8. respectively.

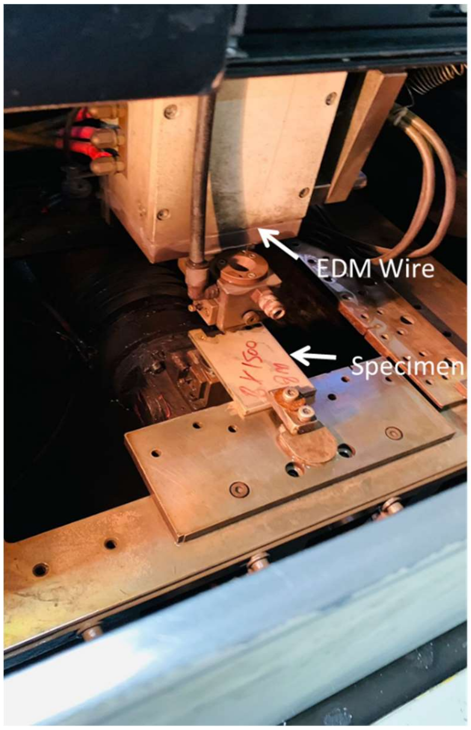


Fig 3.7. EDM wire cutting of Inconel 718 plate

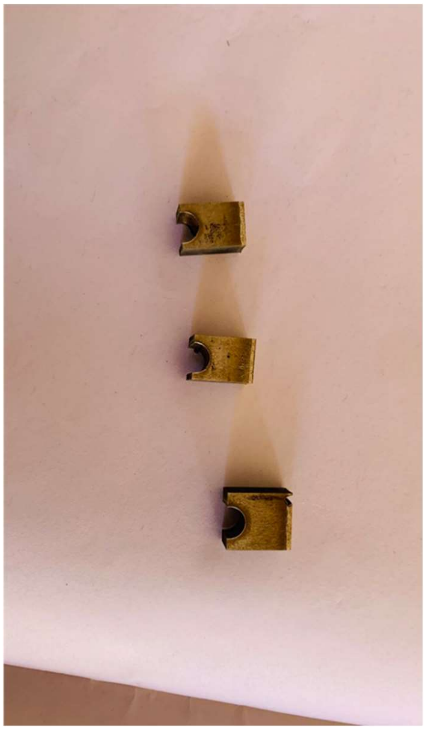


Fig 3.8. Pieces of Inconel 718 after cutting

3.8 SEM AND EDAX ANALYSIS

SEM (Scanning Electron Microscopy) and EDX (Energy Dispersive X-ray Spectroscopy) analysis are powerful tools used in materials science and engineering to obtain information about the surface and elemental composition of a sample. SEM is a technique used to obtain high-resolution images of a sample's surface using a beam of electrons. SEM images can reveal information about the surface morphology, topography, and texture of a sample, allowing for the examination of microstructural features at high magnifications. SEM can also be used to investigate the chemical composition of a sample's surface by coupling it with EDX analysis. Combining SEM with EDX analysis provides valuable information about the surface morphology and elemental composition of a sample. SEM images can reveal the surface features and microstructural properties of a sample, while EDX can provide information about the elemental composition of specific regions of interest within the sample. Together, these techniques can be used to investigate the microstructural features and elemental composition of a wide range of materials, including metals, ceramics, polymers, and composites.

Thus, SEM and EDAX analysis of different ranges of rpm cut pieces are analyzed and microstructure changes are observed and spot analysis chemical composition are noted and studied.

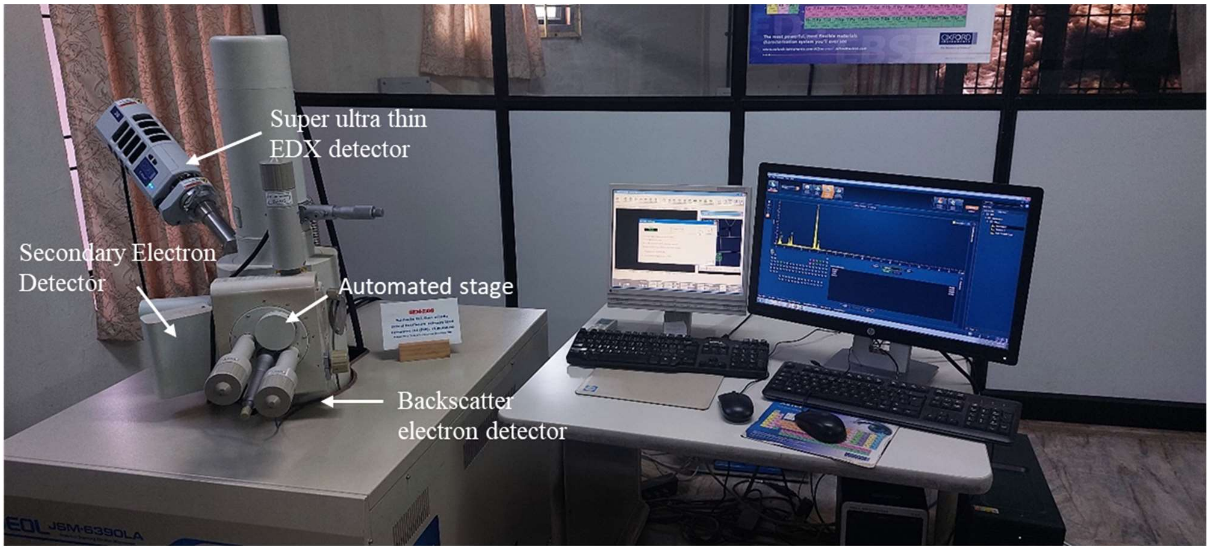


Fig 3.9.SEM and EDAX Analysis equipment

CHAPTER 4

RESULTS AND DISCUSSION

4.1DRILLING FORCE ANALYSIS

4.1.1 DRILLING UNDER DRY CONDITION

- Drilling force at 700 rpm

The drilling process was conducted at a speed of 700 revolutions per minute (rpm). As the drilling began, the force exerted on the drill bit was measured to be 949.608 Newtons (N). This force value is an indication of the resistance encountered by the drill bit as it initially penetrates the material. As the drilling process continues, the force value increases and reaches a maximum of 1051.362 N. This increase in force can be attributed to the drill bit encountering more resistance as it penetrates deeper into the material. The maximum force value is an important parameter that provides insight into the toughness and hardness of the material being drilled. Finally, the drilling process ends when the force value reaches 800.496 N. This indicates that the drill bit has successfully penetrated through the material and reached the other side.

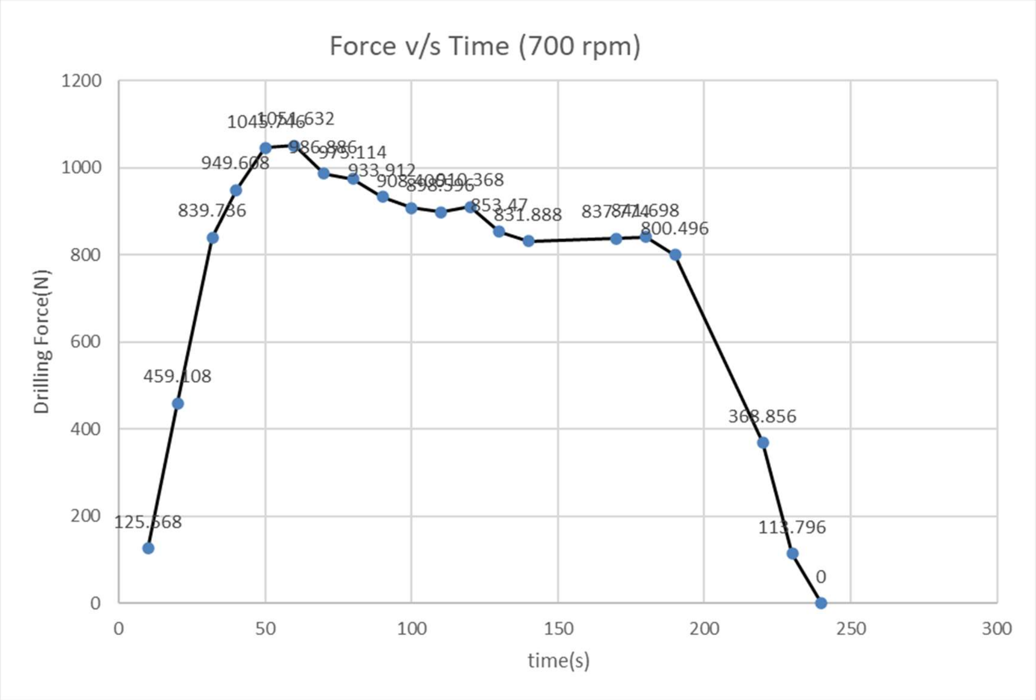


Fig 4.1. Drilling Force v/s time graph for 700 rpm drilling in dry condition.

- Drilling Force at 900 rpm

While drilling at 900 rpm, the force exerted during the drilling process gradually increased from 100.62 N at the starting point of the hole drilling. The maximum force value was recorded at 1226.25 N during the drilling process, and the drilling process concluded when the force value reached 1033.974 N. When comparing the force analysis of drilling at 900 rpm to that of 700 rpm, it was observed that there was an increase in force over time. This indicates that the tool wear during the drilling process increased, and there was a 16% rise in drilling force during the drill bit's penetration into the material being drilled.

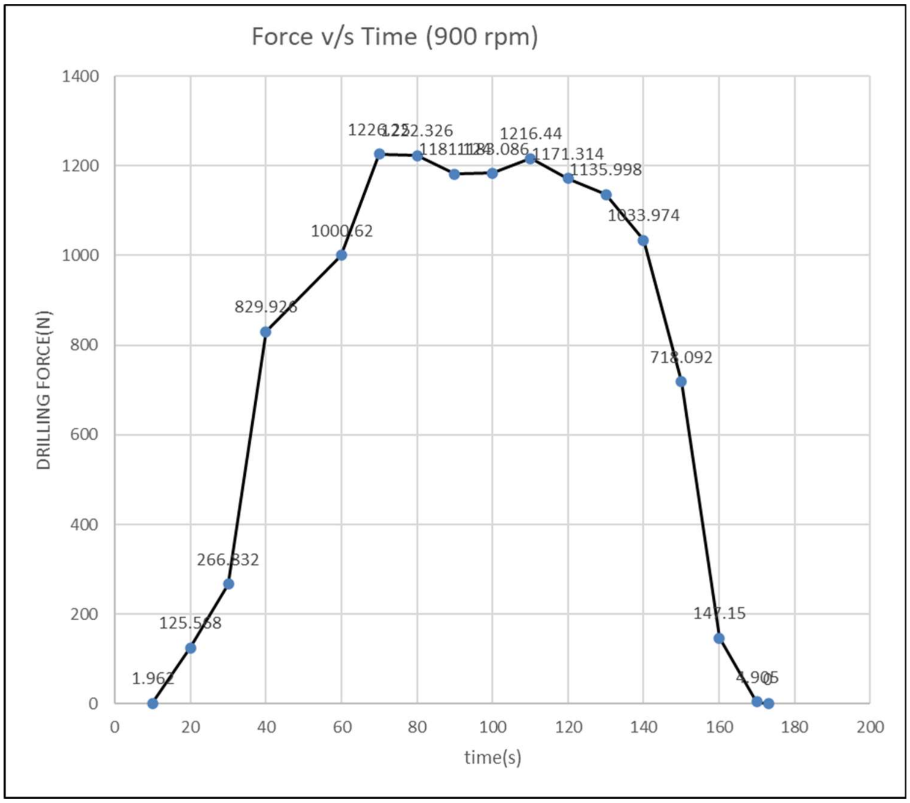


Fig 4.2. Drilling Force v/s time graph for 900 rpm drilling in dry condition.

- Drilling force at 1100rpm

While drilling at 1100 rpm, the force value during the drilling process gradually increased from 935.874 N at the starting point of the hole drilling. The maximum force value was recorded at 1432.26 N during the drilling process, and the drilling process concluded when the force value reached 1039.86 N.

It can be concluded that drilling at 1100 rpm results in a significant increase in drilling force compared to the values observed at 700 rpm and 900 rpm. The force value increased gradually from the starting point of the hole drilling process and reached its maximum at 1432.26 N.

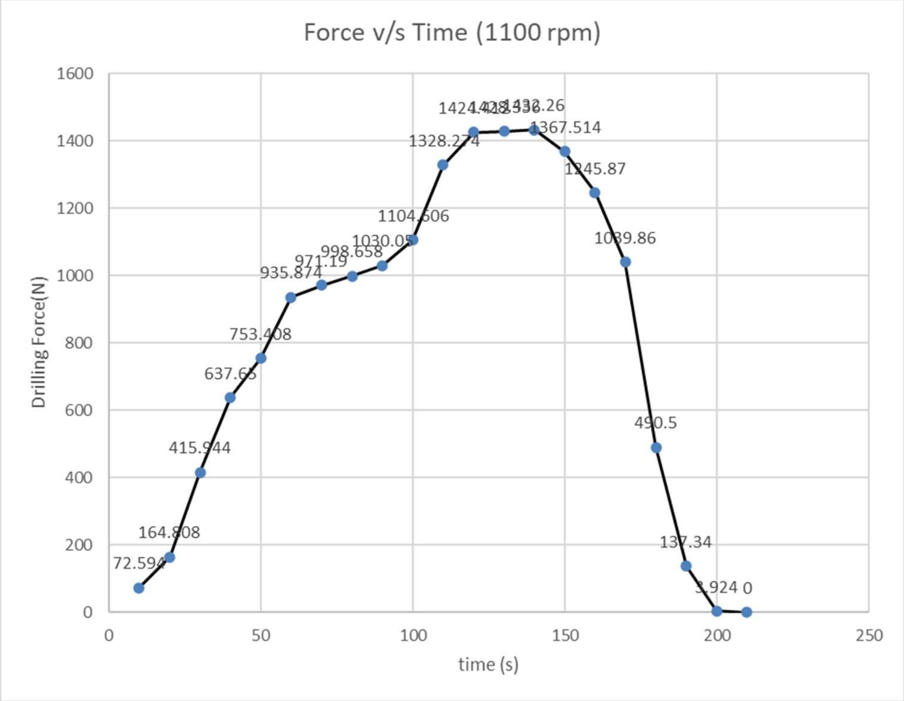


Fig 4.3.Drilling Force v/s time graph for 1100 rpm drilling in dry condition.

- Drilling force at 1800 rpm

The force during the drilling process was analyzed while drilling at 1800 rpm, and the force value gradually increased from 1626.498 N at the beginning of the hole drilling. The maximum force value was recorded at 1885.482 N during the drilling process. Drill bit could not continue drilling the hole as it began to melt due to the extreme force at this point and heat accumulation at this point due to low thermal conductivity of the Inconel 718 plate. As a result, the drilling process was unsuccessful.

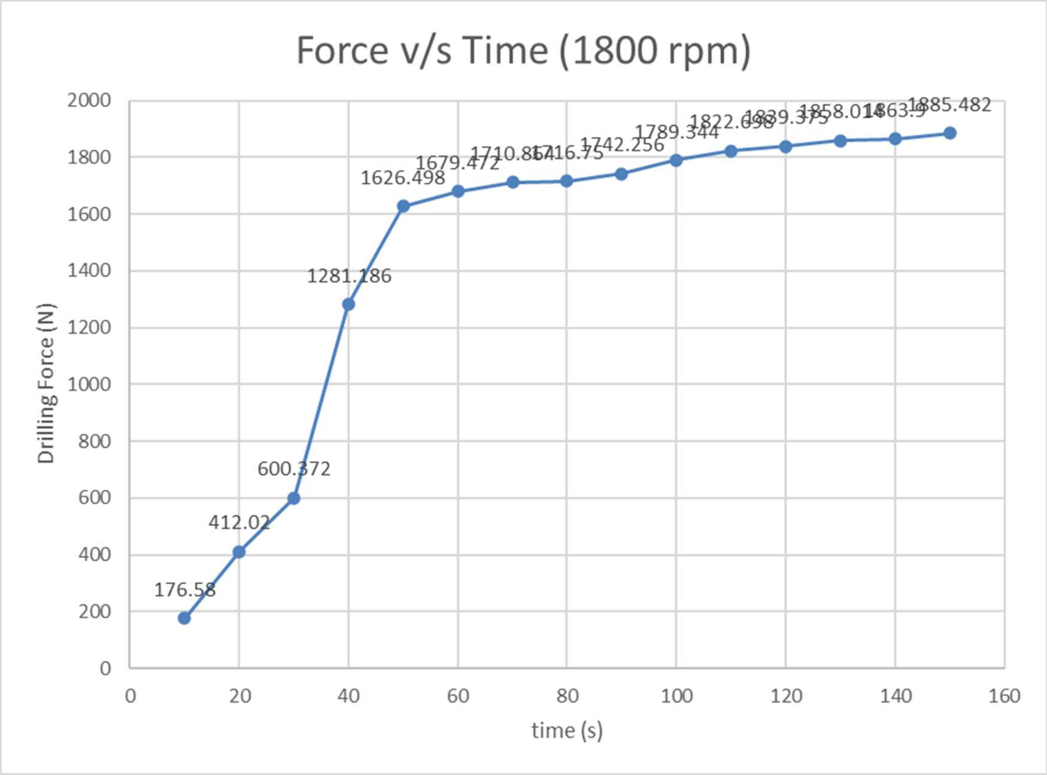


Fig 4.4.Drilling Force v/s time graph for 1800 rpm drilling in dry condition

4.1.2 DRILLING UNDER LN_2 AS COOLANT

Drilling under LN_2 as a coolant involves using liquid nitrogen to cool the drill bit during the drilling process. The cooling effect of LN_2 helps to reduce the temperature of the cutting zone, which in turn, reduces the thermal stresses on the material being drilled. This can lead to less damage to the material and improved surface finish of the drilled hole.

One advantage of using LN_2 as a coolant during drilling is that it can increase the tool life of the drill bit. The cooling effect of LN_2 can reduce the friction between the drill bit and the material being drilled, thereby reducing wear and tear on the drill bit. This can also lead to less need for tool replacement, reducing overall costs.

Another advantage is that the use of LN_2 as a coolant can lead to improved chip evacuation during the drilling process. The cooling effect of LN_2 can cause the chips to be more brittle, which can help them break away more easily from the drilled hole. This can lead to less clogging of the drill bit and improved drilling efficiency.

Fig 4.5.Drilling Inconel 718 using Liquid Nitrogen as coolant

- Drilling force at 700 rpm

When drilling at a speed of 700 rpm with liquid nitrogen as a coolant, the force required to drill the hole increases from 706.3 N at the beginning to a maximum of 1432.6 N during the process. The drilling process ends when the force value drops to 882.9 N.

In comparison to the dry condition, the use of liquid nitrogen as a coolant during drilling at 700 rpm increases the force required to drill the hole. This is evident from the maximum force value during the process, which is higher in the case of liquid nitrogen cooling (1432.6 N) compared to the dry condition. However, the drilling process stops at a similar force value in both cases (882.9 N).

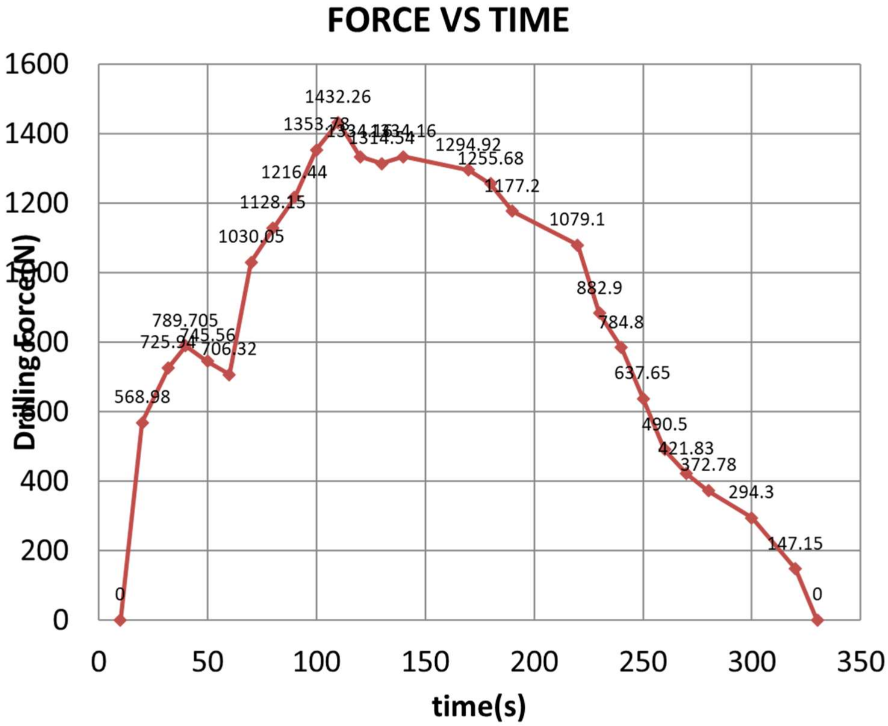


Fig 4.6. Drilling Force v/s time graph for 700 rpm drilling using LN_2 as coolant

- Drilling force at 900 rpm

During the drilling process at 900 rpm with liquid nitrogen as the coolant, the force required to drill the hole increases from 863.28 N at the start to a maximum of 1473.62 N. The process comes to a halt when the force value drops to 839.76 N.

When compared to 700 rpm drilling with liquid nitrogen coolant, the drilling force value required to drill a hole is higher in the 900 rpm case. The maximum force value during the process (1473.62 N) is also higher when compared to 700 rpm (1432.6 N). In both cases, the drilling process ends at a similar force value (839.76 N for 900 rpm and 882.9 N for 700 rpm).

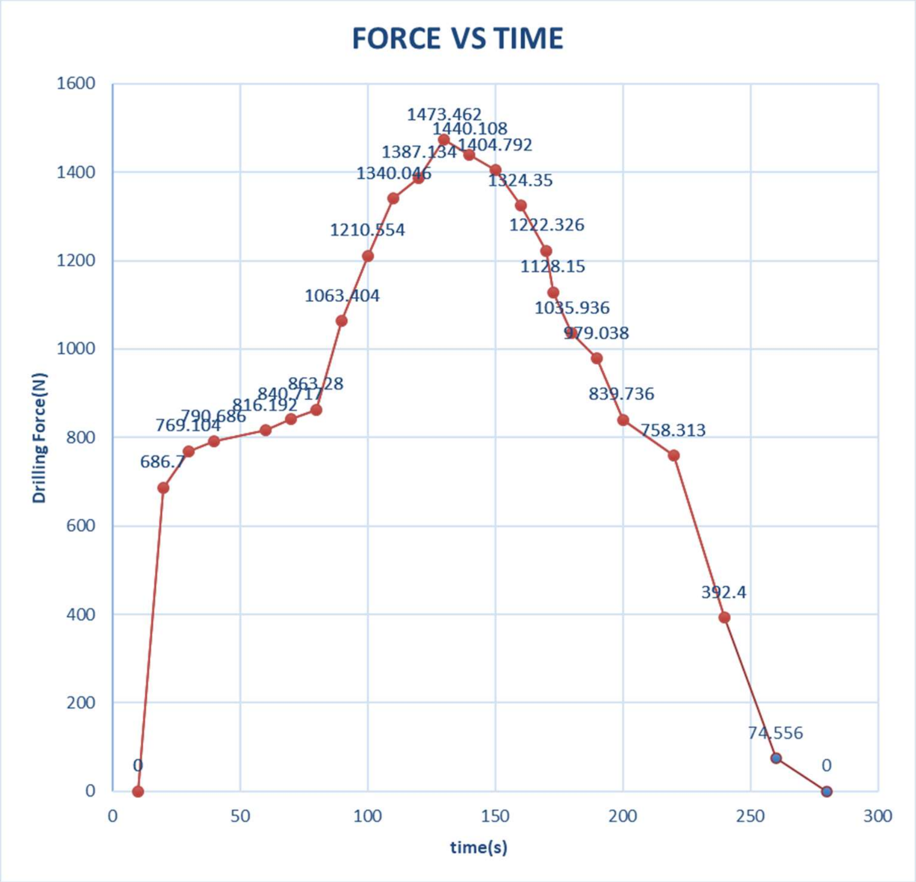


Fig 4.7. Drilling Force v/s time graph for 900 rpm drilling using LN_2 as coolant

- Drilling force at 1100 rpm

When drilling at 1100 rpm with liquid nitrogen as the coolant, the force required to drill the hole increases from 1081.062 N at the beginning to a maximum of 1976.715 N during the process. The drilling process stops when the force value drops to 882.9 N.

When compared with700 rpm, it is observed that the drilling force required to drill the hole is significantly higher in the 1100 rpm case with liquid nitrogen coolant. The maximum force value during the process (1976.715 N) is considerably higher compared to both the 700 rpm and 900 rpm.

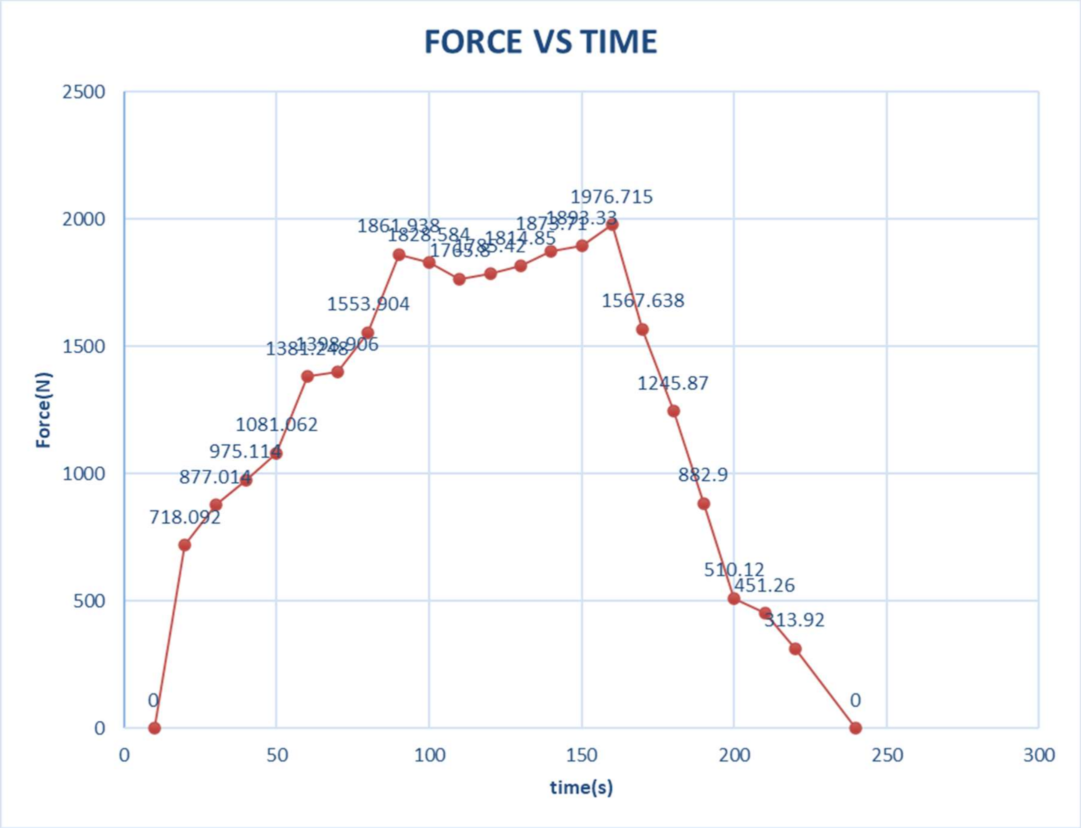


Fig 4.8. Drilling Force v/s time graph for 1100 rpm drilling using LN_2 as coolant

4.2 SEM IMAGE ANALYSIS

4.2.1 SEM IMAGE ANALYSIS UNDER DRY CONDITION

- SEM image at 700 rpm

When drilling at 700rpm without any coolant, a significant amount of delamination is observed. This delamination is due to the higher stress induced during the drilling process, which results from the lower drilling speed. At this lower speed, there is higher deflection of the material, which leads to higher friction rates during machining. As a result, spalling rates are higher, and both cracks and delamination occur more frequently.Furthermore, irregular plowing grooves are found during dry drilling at 700rpm because there is no constant friction force during machining at this lower speed. The shapes of these plowing grooves are unpredictable and may vary based on the material being drilled, the type of cutting tool used, and other factors.

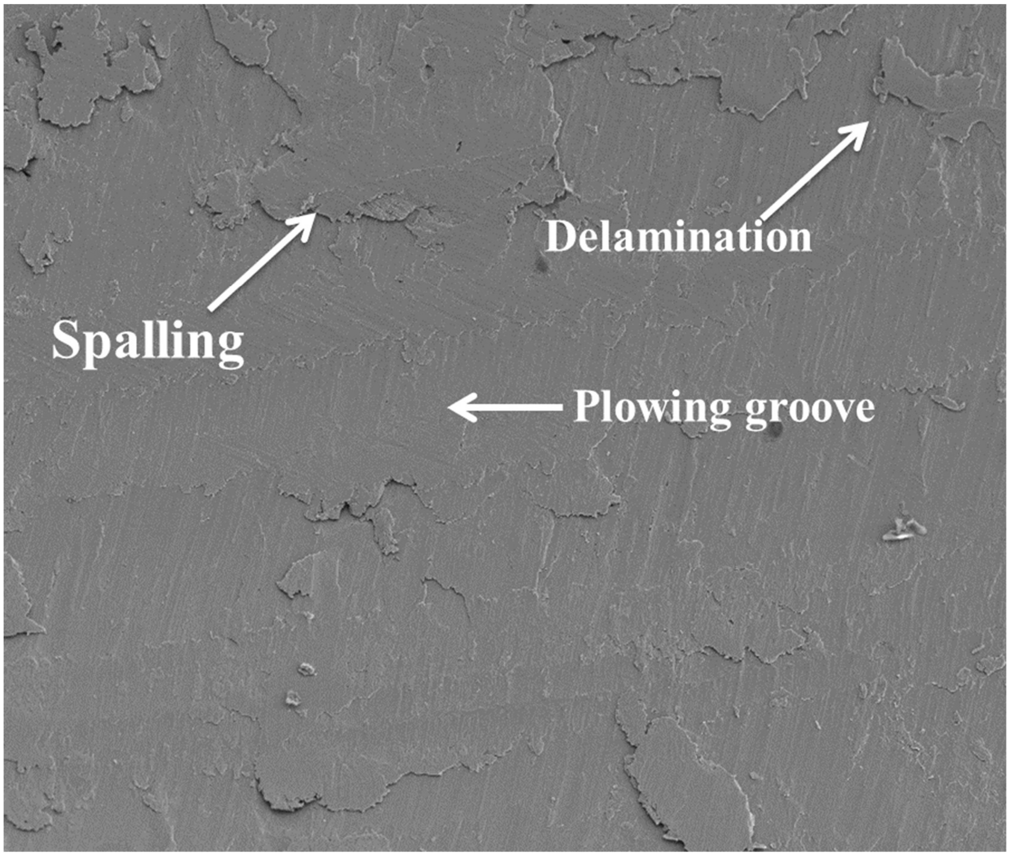


Fig 4.9. SEM image of Inconel 718 specimen at 700 rpm drilled hole surface under dry condition

- SEM Image at 1100 rpm

When drilling at 1100rpm without any coolant, there is very little delamination observed because the stress induced during drilling is lower due to the higher drilling speed. As a result, there is less deflection of the material during the drilling process.

Plowing grooves are found in regular shapes during dry drilling at 1100rpm because the friction produced during the drilling process is more consistent across the material being drilled due to the higher drilling speed. This results in more uniform grooves being formed during the drilling process.A potential issue that can occur during dry drilling at higher speeds such as 1100rpm is the formation of cracks on the surface of the drilled hole. This is due to the dislocation of grains in the alloy as a result of the high stresses generated during the drilling process.

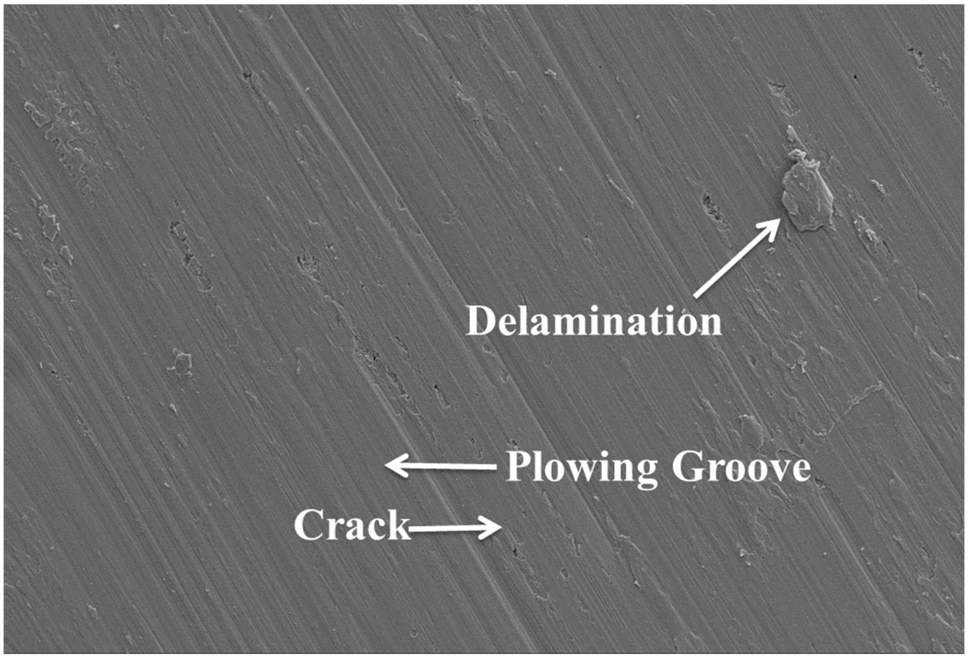


Fig 4.10. SEM image of Inconel 718 specimen at 1100 rpm drilled hole surface under dry condition

4.2.2 SEM IMAGE ANALYSIS USING LN$_2$ AS COOLANT CONDITION

- SEM image at 700 rpm

When liquid nitrogen is used as a coolant during the drilling process under 700 rpm, irregular plowing grooves are observed to occur less frequently on the machined hole surface. This suggests that the surface has less wear as compared to dry drilling processes.Spalling is found to occur more frequently on the surface of the drilled hole due to the use of liquid nitrogen. This is because the frequent cooling and heating cycles during the drilling process can cause thermal stresses on the material, leading to changes in the microstructure and eventually spalling on the hole surface.The use of liquid nitrogen as a coolant during drilling under 700 rpm leads to frequent deposition of carbide particles. This can be attributed to the reduction in the temperature of the cutting zone, which can cause the material being drilled to harden and subsequently result in carbide deposition.

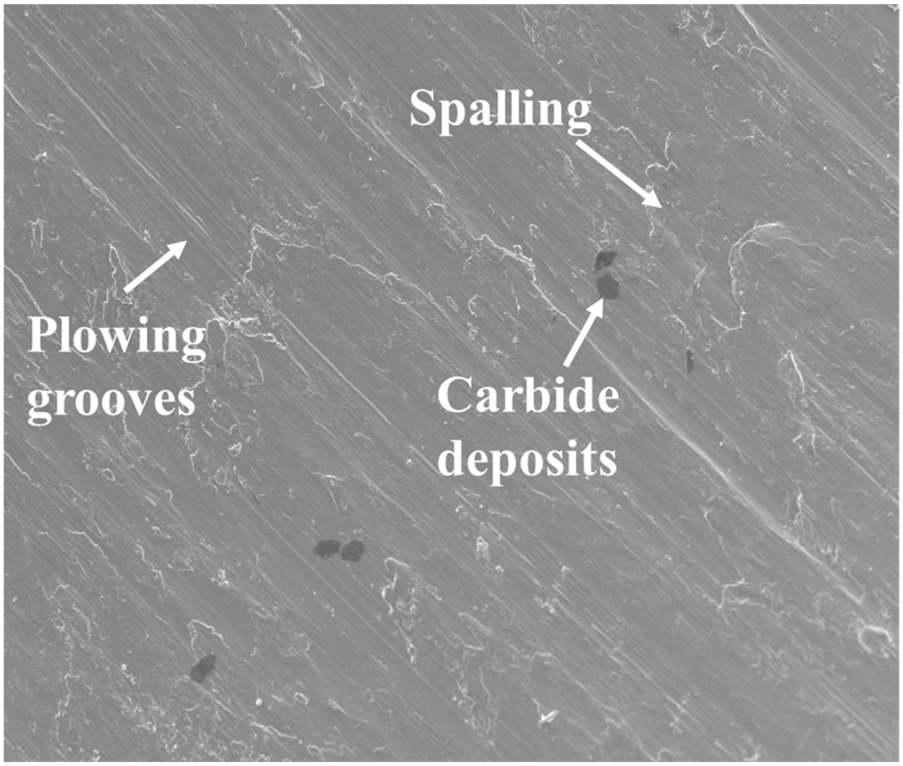


Fig 4.11. SEM image of Inconel 718 specimen at 700 rpm drilled hole surface using LN$_2$ as coolant

- SEM image at 1100 rpm

When liquid nitrogen is used as a coolant during drilling at 1100 rpm, the plowing grooves formed on the machined surface are irregular in shape, which may indicate a higher level of structural strength in the material. Dark regions observed during the process contain gamma phases, indicating that the material has a high capacity to maintain its strength even under stressful conditions.

Gamma phases significantly enhance the material's high-temperature strength, making it a popular choice in applications where extreme conditions are expected. The presence of gamma phases in the dark regions suggests that the material retains its strength even under the high stresses generated during the drilling process.The irregular plowing grooves observed during drilling with liquid nitrogen as a coolant at 1100 rpm suggest that the material being drilled may be more difficult to cut, but also that it may be more resilient under high-stress conditions.

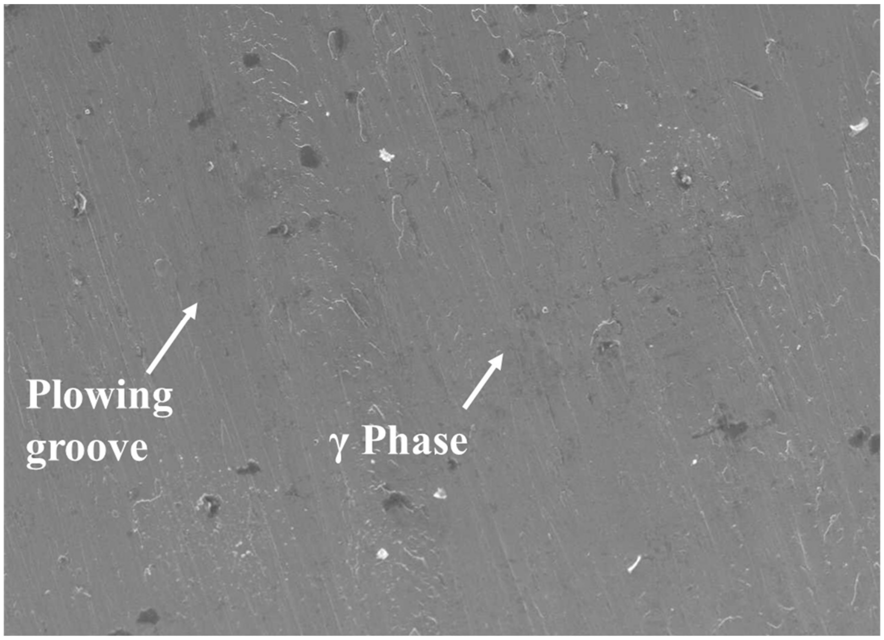


Fig 4.12. SEM image of Inconel 718 specimen at 1100 rpm drilled hole surface using LN_2 as coolant

4.3 EDS ANALYSIS

4.3.1 EDS ANALYSIS UNDER DRY CONDITION

- EDS Spot analysis of 700 rpm

The information obtained from the EDS spot analysis at 700 rpm can provide insight into the elemental composition of the sample in the analyzed spot. Specifically, the energy of the X-rays detected by the EDS detector corresponds to the energy of the characteristic X-rays emitted by the elements present in the sample. By analyzing the energy and intensity of these X-rays, it is possible to determine the elemental composition of the sample in the analyzed spot.

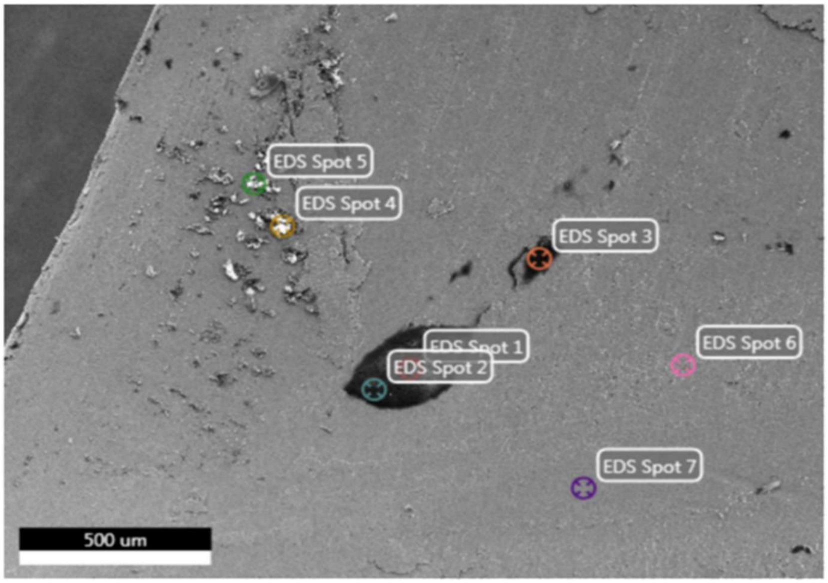


Fig 4.13.EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under dry condition

The EDS spot analysis was done for 700 rpm dry drilling and spot image analysis is shown in figure 4.13. and its respective chemical composition figures and tables are listed below for each spot. EDS spot 1 and 2 chemical composition of 700 rpm dry drilling is shown in table 4.1. and its corresponding graph is shown in figure 4.14.

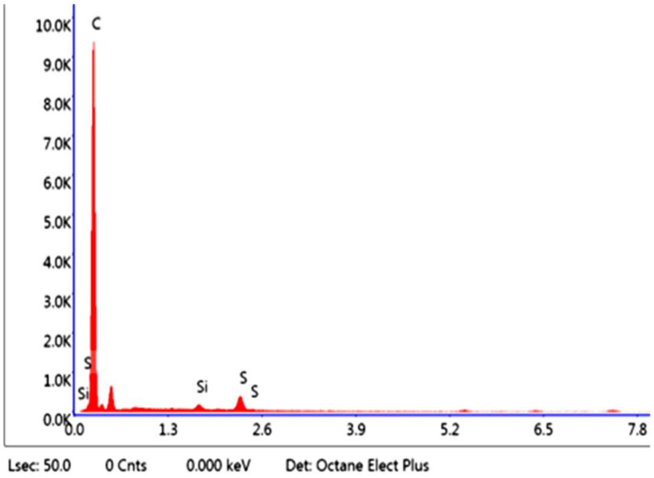


Fig 4.14. Graph of EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under dry condition for Spot 1 and 2

Table 4.1. EDS Spot 1 and 2 (700 rpm dry drilling)

Element	Weight %	Atomic %
C	97.20	98.90
Si	0.62	0.27
S	2.18	0.83

In Spot 1 and 2 there is no Nickel or chromium content which shows that there is no property of the alloy is shown and drilling altered the chemical composition. EDS spot 3 chemical composition of 700 rpm dry drilling is shown in table 4.2. and its corresponding graph is shown in figure 4.15.

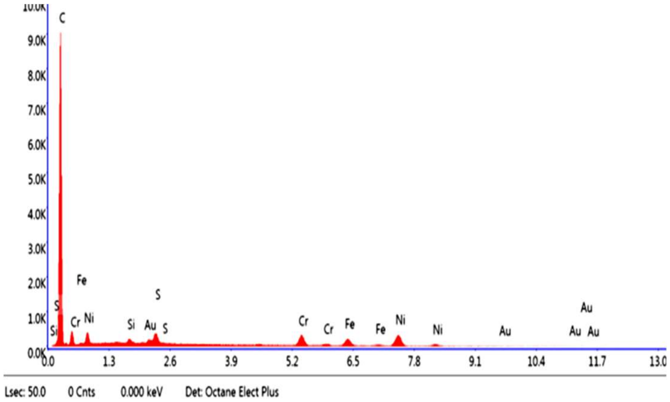


Fig 4.15. Graph of EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under dry condition for Spot 3

Table 4.2. EDS Spot 3 (700 rpm dry drilling)

Element	Weight %	Atomic %
Ni	7.45	1.74
Cr	3.64	0.96
Fe	3.12	0.77
Au	0.01	0
C	83.92	95.72
Si	0.40	0.19
S	1.46	0.63

In Spot 3 there is low concentration of Ni about 7.45% which shows depreciation of its concentration from original amount which shows large alteration from its original value and there is no property of Inconel 718 alloy.EDS spot 3 chemical composition of 700 rpm dry drilling is shown in table 4.3. and its corresponding graph is shown in figure 4.16.

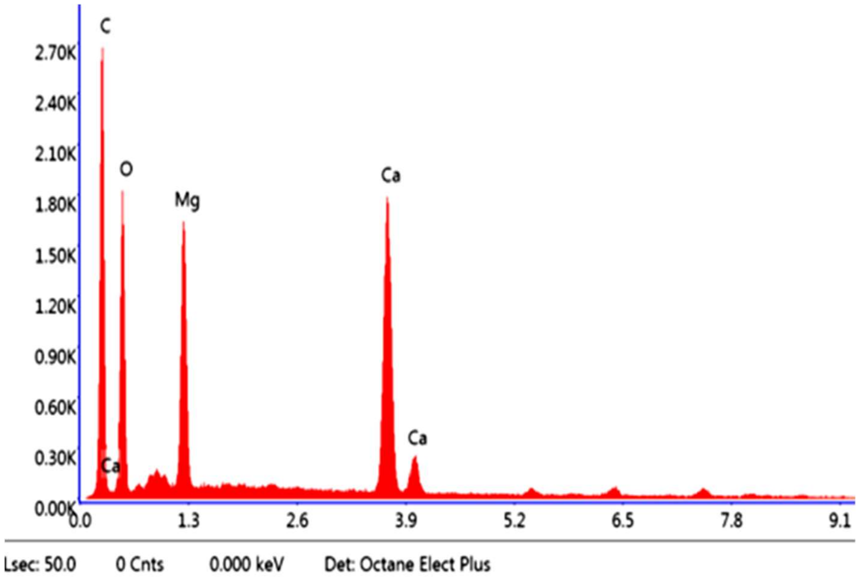


Fig 4.16.Graph of EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under dry condition for Spot 5

Table 4.3.EDS Spot 5 (700 rpm dry drilling)

Element	Weight %	Atomic %
Mg	8.67	5.77
Ca	18.14	7.32
O	34.76	35.15
C	38.44	51.77

From this EDS Spot analysis of spot 3 it is evident that there is no Ni content present in the particular spot thus the alloy property is changed during dry drilling.EDS spot 6 chemical composition of 700 rpm dry drilling is shown in table 4.4. and its corresponding graph is shown in figure 4.17.

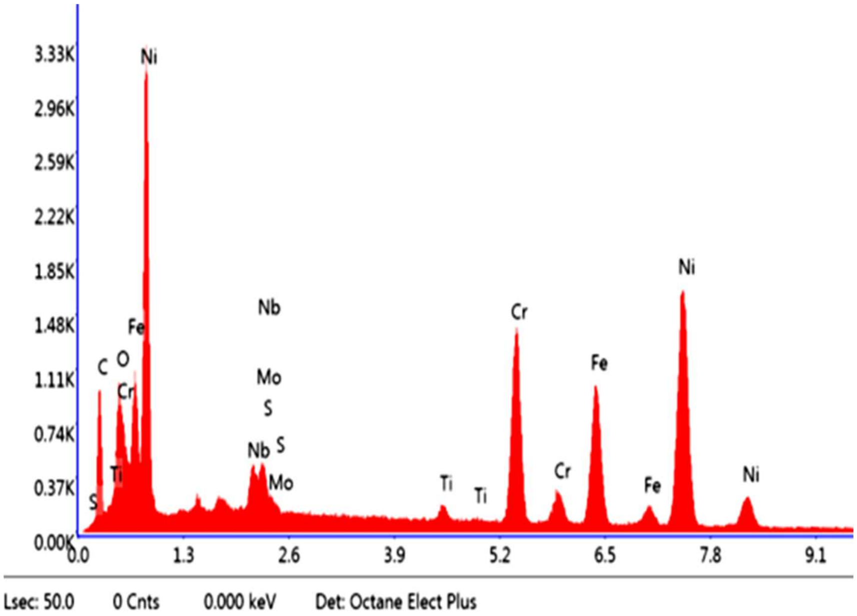


Fig 4.17. Graph of EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under dry condition for Spot 6

Table 4.4. EDS Spot 6 (700 rpm dry drilling)

Element	Weight %	Atomic %
Ni	39.47	21.38
Cr	15.82	9.68
Fe	18.79	8.99
Nb	3.25	1.11
Mo	1.81	0.60
Ti	0.91	0.61
C	18.27	48.39

The EDS analysis of Spot 5 reveals that the percentage of nickel is closer to the original composition, but it is still quite low. This suggests that the dry drilling process at 700 rpm has caused significant changes to the chemical composition of the material. Thus combining these value the EDS Spot average is shown in Table 4.5.

Table 4.5. EDS Average (700 rpm Dry condition)

Element	Weight %	Atomic %
Ni	11.73	5.78
Cr	4.865	2.7
Fe	4.725	2.7
C	59.46	73.7
Mn	0	0
Si	0.26	0.115
S	0.91	0.365

The EDS analysis of the Inconel 718 plate drilled at 700 rpm without any coolant reveals a significant decline in its chemical composition. The analysis shows a major reduction in the nickel (Ni) content of the plate, which is a key element in the composition of Inconel 718. At the same time, the carbon (C) content of the plate is found to increase significantly. This change in chemical composition could affect the mechanical properties of the material, including its strength and durability. It may also impact the performance of the part or component being drilled, leading to potential failures or malfunctions. Therefore, it is important to consider the impact of drilling conditions on the chemical composition and resulting properties of the material being drilled.

- EDS Spot Analysis of 1100 rpm

EDS Spot analysis for higher i.e., 1100 rpm is done and the results are taken for comparing it with the lowest rpm (700 rpm) which was taken among the experiment. the EDS Spot analysis image for 1100 rpm dry drilling is shown in figure 4.18.

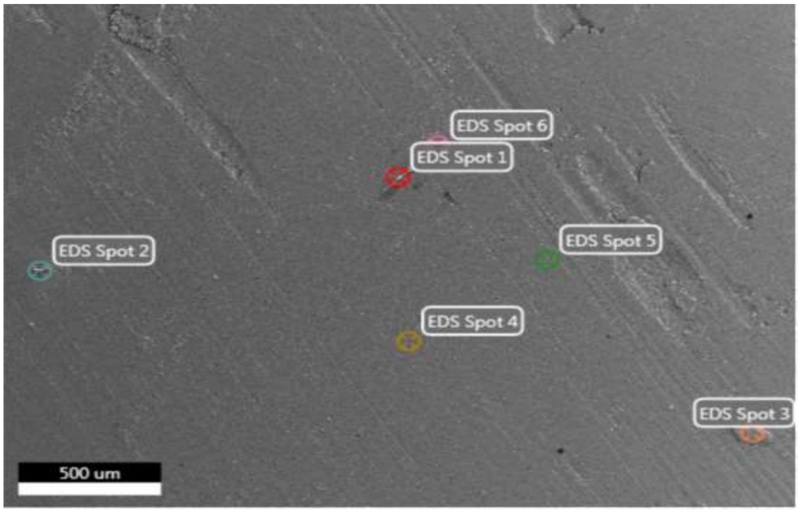


Fig 4.18.EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface under dry condition

EDS spot 1 chemical composition of 1100 rpm dry drilling is shown in table 4.6. and its corresponding graph is shown in figure 4.19.

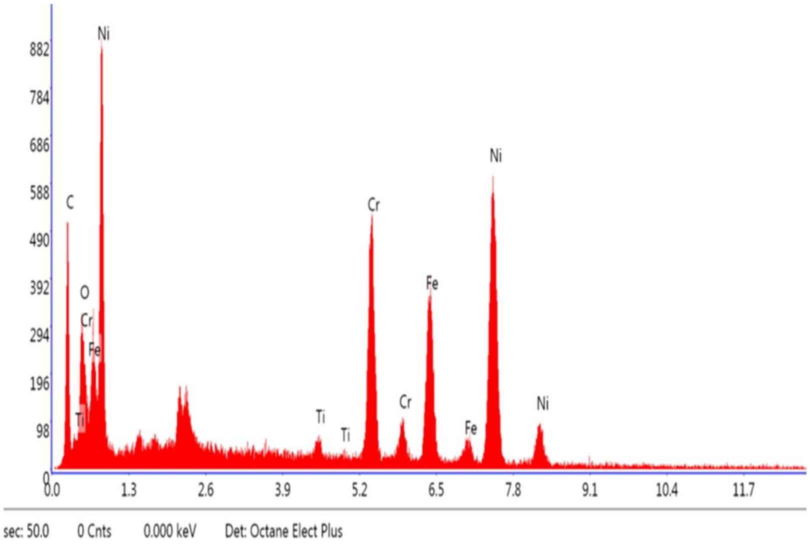
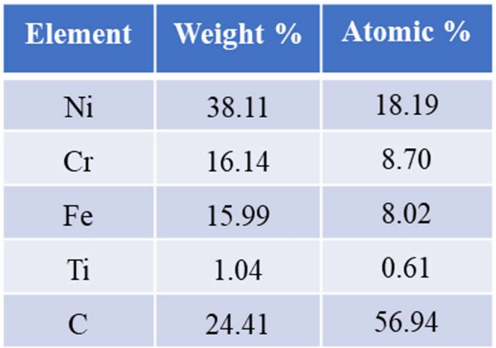


Fig 4.19.Graph of EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface under dry condition for Spot 1

Table 4.6. EDS Spot 1 (1100 rpm dry drilling)



Element	Weight %	Atomic %
Ni	38.11	18.19
Cr	16.14	8.70
Fe	15.99	8.02
Ti	1.04	0.61
C	24.41	56.94

From EDS Spot Analysis for 1100 rpm dry drilling of Spot 1 there is improvement in Nickel content with a percentage of 38.11 which shows that chemical composition of alloy is slightly retained.EDS spot 3 chemical composition of 1100 rpm dry drilling is shown in table 4.7. and its corresponding graph is shown in figure 4.20.

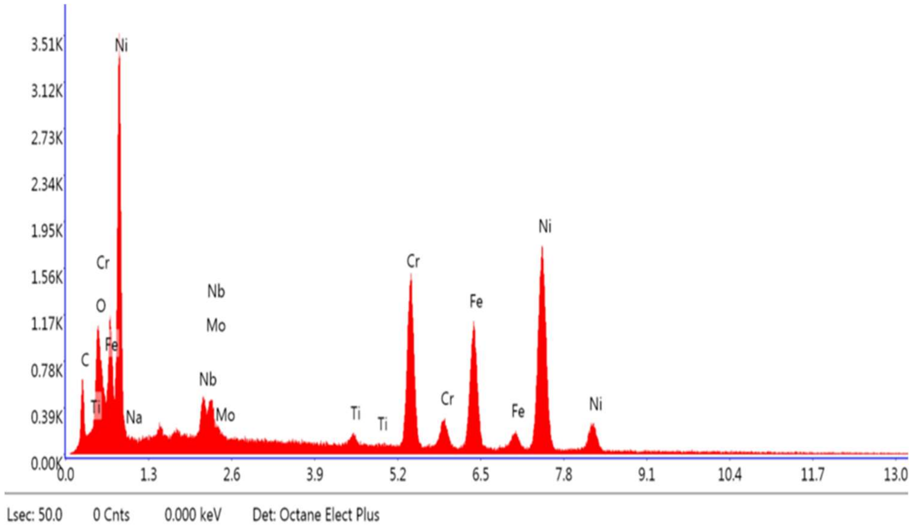


Fig 4.20.Graph of EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface under dry condition for Spot 3

Table 4.7. EDS Spot 3 (1100 rpm dry drilling)

Element	Weight %	Atomic %
Ni	40.92	24.82
Cr	16.77	16.77
Fe	17.03	10.86
C	12.38	36.69
Mo	1.97	0.73
Ti	0.90	0.67

The EDS analysis of Spot 3 shows that the composition is very similar to that of Spot 1, indicating that there has been little alteration in the material's properties. This suggests that as the rpm increases, there is a significant degradation in the chemical composition of the alloy.EDS spot 5 chemical composition of 1100 rpm dry drilling is shown in table 4.8. and its corresponding graph is shown in figure 4.21.

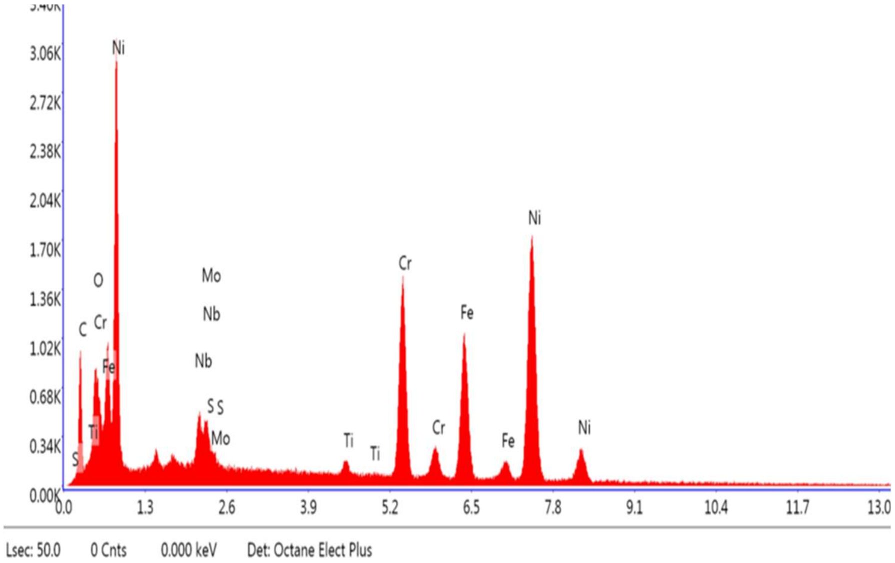
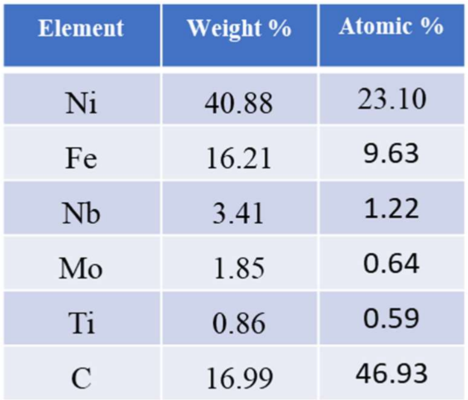


Fig 4.21.Graph of EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface under dry condition for Spot 5

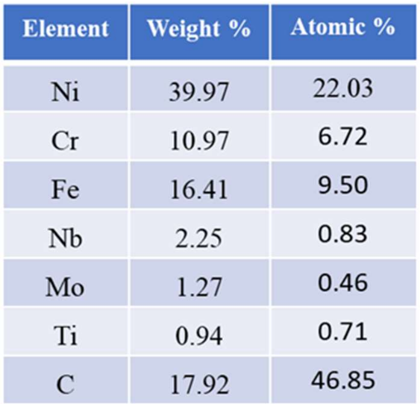
Table 4.8. EDS Spot 5 (1100 rpm dry drilling)



Element	Weight %	Atomic %
Ni	40.88	23.10
Fe	16.21	9.63
Nb	3.41	1.22
Mo	1.85	0.64
Ti	0.86	0.59
C	16.99	46.93

The analysis of spot 5 using EDS shows that the Ni content percentage is enhanced when dry drilling is done at higher rpm, which brings it closer to the original chemical composition. As a result, an average of these spots was calculated for further examination. Table 4.9 presents the EDS Spot average that was computed for further analysis.

Table 4.9. EDS Average (1100 rpm Dry Condition)



Element	Weight %	Atomic %
Ni	39.97	22.03
Cr	10.97	6.72
Fe	16.41	9.50
Nb	2.25	0.83
Mo	1.27	0.46
Ti	0.94	0.71
C	17.92	46.85

From EDS analysis it is seen that the nickel percentage is lower compared to the original composition, indicating that some of the nickel has been removed during the drilling process. However, the carbon content is lower compared to the drilling at 700 rpm without coolant, which could be due to the higher drilling speed and the resulting lower residence time of the material in the cutting zone. It is interesting to note that the iron and chromium content are retained at relatively high levels, which suggests that the material retains its strength and corrosion resistance even after drilling at high speed without coolant.

4.3.2 EDS ANALYSIS USING LIQUID NITROGEN AS COOLANT CONDITION

- EDS Spot Analysis of 700 rpm

EDS analysis of 700 rpm drilling using LN_2 as coolant is carried out and its chemical composition is identified using EDS spot analysis and the image for the spot analysis is shown in figure 4.22.

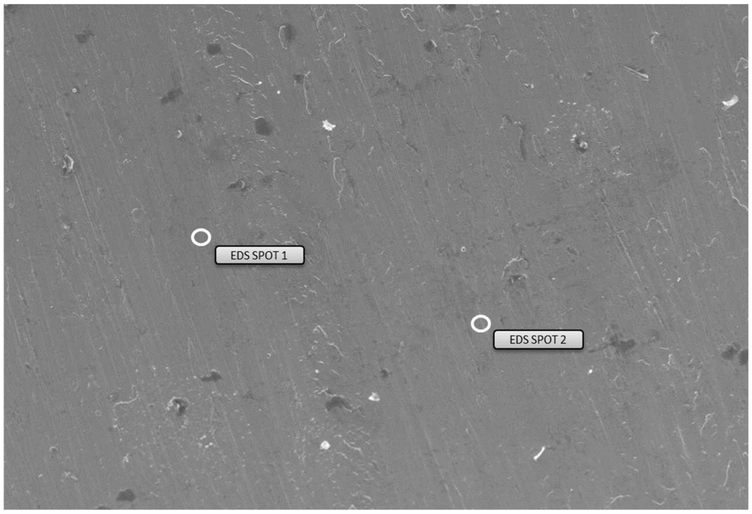


Fig 4.22.EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface using LN_2 as coolant

EDS spot 1 chemical composition of 700 rpm drilling using LN2 as coolant is shown in table 4.10. and its corresponding graph is shown in figure 4.23.

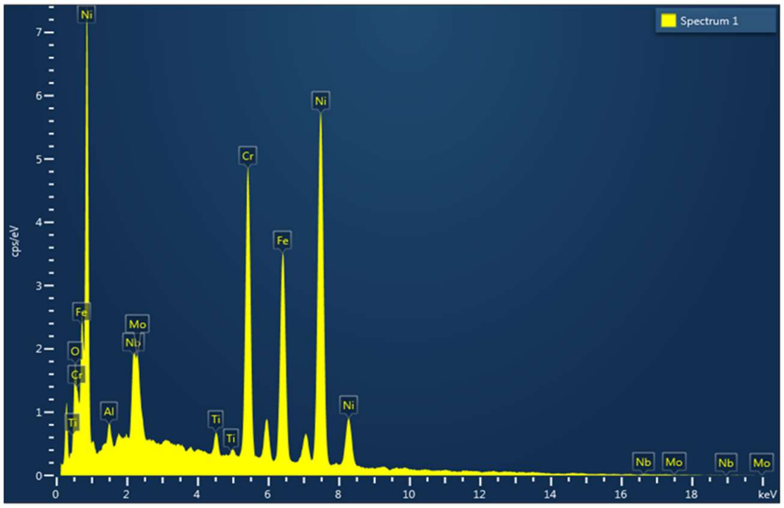


Fig 4.23. Graph of EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under using LN_2 as coolant for Spot 1

Table 4.10. EDS Spot 1 (700 rpm LN$_2$ as coolant Condition)

Element	**Weight %**	**Atomic %**
Ni	49.22	45.02
Cr	18.16	18.16
Fe	18.7	17.98
Nb	5.55	3.21
Mo	3.23	1.81
Ti	1.27	1.42
Al	0.87	1.74
O	3	10.06

While compared to dry drilling in 700 rpm LN$_2$ assisted drilling there is increase in Ni content which shows there is no chemical composition change while compared to original alloy composition.EDS spot 2 chemical composition of 700 rpm drilling using LN$_2$ as coolant is shown in table 4.11. and its corresponding graph is shown in figure 4.24.

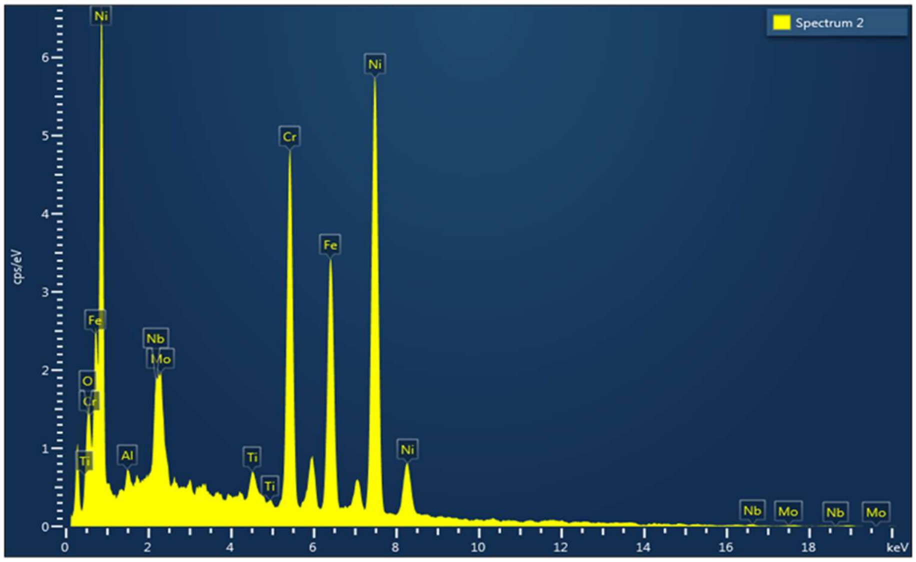
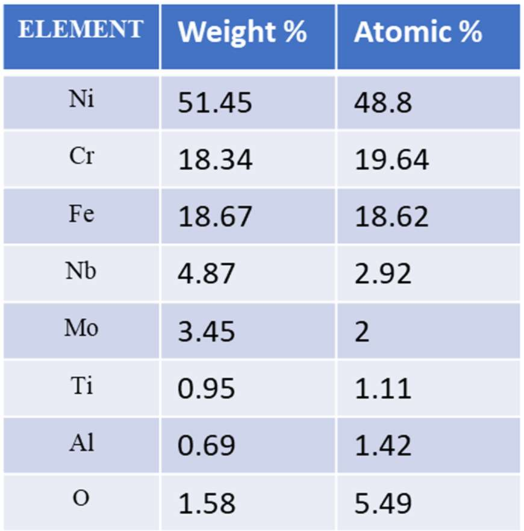


Fig 4.24. Graph of EDS Analysis of Inconel 718 specimen at 700 rpm drilled hole surface under using LN$_2$ as coolant for Spot 2

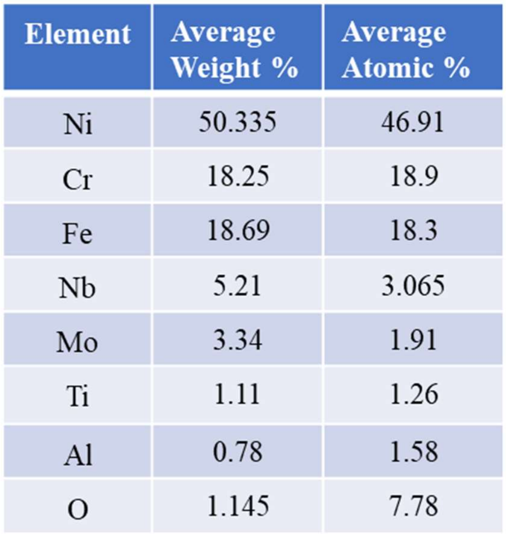
Table 4.11.EDS Spot 2 (700 rpm LN_2 as coolant Condition)



ELEMENT	Weight %	Atomic %
Ni	51.45	48.8
Cr	18.34	19.64
Fe	18.67	18.62
Nb	4.87	2.92
Mo	3.45	2
Ti	0.95	1.11
Al	0.69	1.42
O	1.58	5.49

From EDS Spot 2 analysis there is no concentration change from the spot 1 which shows improved hole during drilling. EDS average is obtained and is shown in Table 4.12

Table 4.12 EDS Average (700 rpm LN_2 as coolant condition)



Element	Average Weight %	Average Atomic %
Ni	50.335	46.91
Cr	18.25	18.9
Fe	18.69	18.3
Nb	5.21	3.065
Mo	3.34	1.91
Ti	1.11	1.26
Al	0.78	1.58
O	1.145	7.78

The EDS analysis showed that the chemical composition of the alloy was not much changed compared to the original alloy.The EDS analysis revealed that the nickel percentage was about 50.335%, which is higher than the nickel content observed in dry drilling conditions. The high nickel content can be attributed to the use of liquid nitrogen as a coolant, which can prevent the material from undergoing high thermal stresses that can cause material deformation or melting.

Moreover, the analysis showed that carbon content was not much observed in this analysis. This implies that the use of liquid nitrogen as a coolant does not result in the deposition of carbide particles on the machined surface, which is observed in dry drilling conditions. The absence of carbide particles is a positive outcome as it can reduce the wear and tear of the tool and increase the longevity of the machining process.

- EDS Spot Analysis of 1100 rpm

EDS analysis of 700 rpm drilling using LN_2 as coolant is carried out and its chemical composition is identified using EDS spot analysis and the image for the spot analysis is shown in figure 4.25.

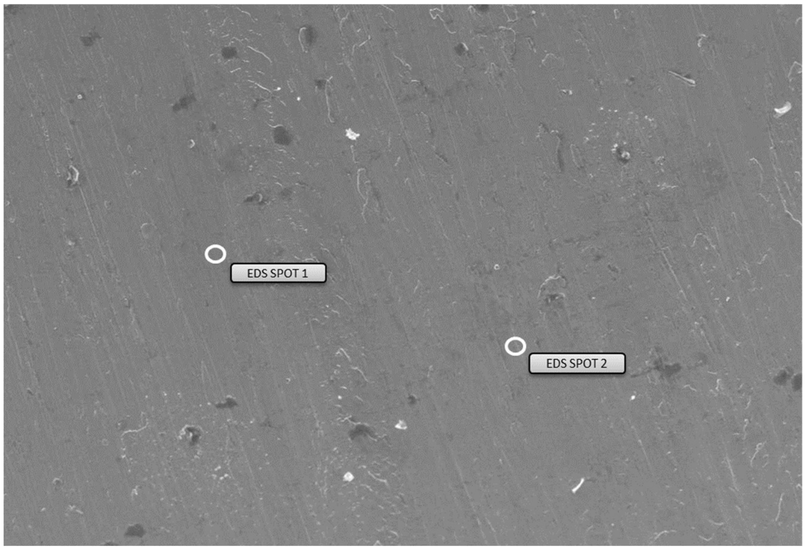


Fig 4.25.EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface using LN_2 as coolant

EDS spot 1 chemical composition of 700 rpm drilling using LN2 as coolant is shown in table 4.12. and its corresponding graph is shown in figure 4.26.

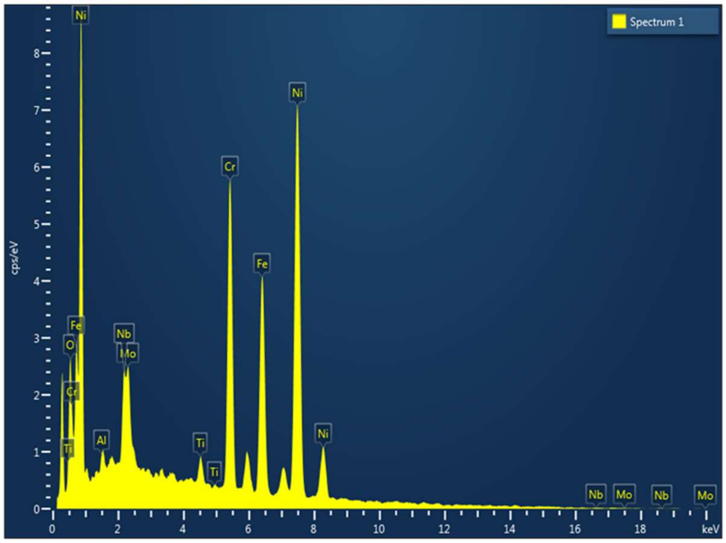


Fig 4.26. Graph of EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface under using LN_2 as coolant for Spot 1

Table 4.13.EDS Spot 1 (1100 rpm LN_2 as coolant Condition)

Element	Weight %	Atomic %
Ni	49.42	42.83
Cr	17.82	17.44
Fe	17.96	16.37
Nb	4.72	2.59
Mo	3.46	1.83
Ti	0.74	0.79
Al	0.41	0.78
O	5.46	17.37

From EDS Spot 1 there is no change in chemical composition from its original concentration thus the hole quality is improved using LN_2 assisted drilling. EDS spot 2 chemical composition of 700 rpm drilling using LN_2 as coolant is shown in table 4.14. and its corresponding graph is shown in figure 4.27.

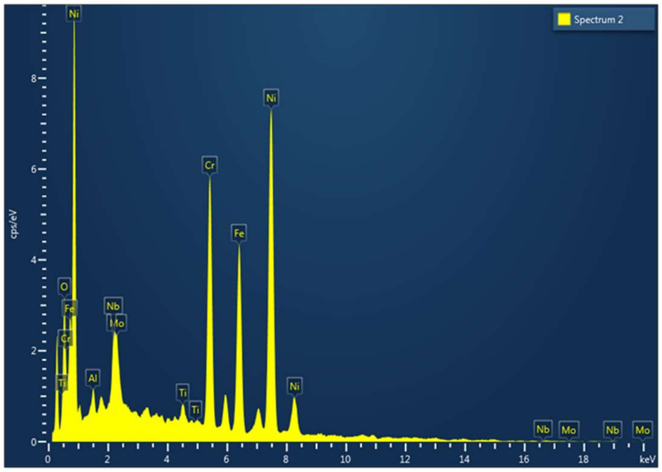


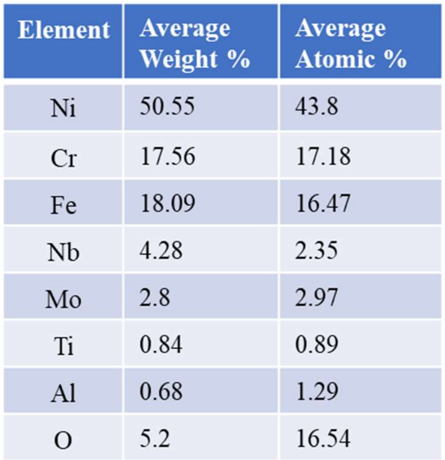
Fig.4.27. Graph of EDS Analysis of Inconel 718 specimen at 1100 rpm drilled hole surface under using LN_2 as coolant for Spot 2

Table 4.14.EDS Spot 2 (1100 rpm LN_2 as coolant Condition)

Element	Weight %	Atomic %
Ni	51.67	44.76
Cr	17.29	16.91
Fe	18.21	16.58
Nb	3.85	2.11
Mo	2.14	1.14
Ti	0.94	1
Al	0.95	1.79
O	4.94	15.71

From EDS Spot 2 also there is no change in chemical composition from its original concentration thus the hole quality is improved using LN_2 assisted drilling. EDS average is calculated and is shown in table 4.15.

Table 4.15 EDS Average (1100 rpm LN_2 as coolant Condition)



Element	Average Weight %	Average Atomic %
Ni	50.55	43.8
Cr	17.56	17.18
Fe	18.09	16.47
Nb	4.28	2.35
Mo	2.8	2.97
Ti	0.84	0.89
Al	0.68	1.29
O	5.2	16.54

The EDS analysis of drilling using liquid nitrogen as coolant at 1100 rpm showed that the chemical composition of Inconel 718 alloy was not significantly changed in comparison to the drilling at 700 rpm using liquid nitrogen as a coolant. The analysis showed that the percentage of nickel in the alloy was 50.55% and the percentage of chromium was 17.56%, which were similar to the values obtained in the previous analysis. This suggests that using liquid nitrogen as a coolant at 1100 rpm did not significantly alter the chemical composition of the Inconel 718 alloy, and the alloy retained its original properties.

CHAPTER 5

CONCLUSIONS

Drilling was carried out under both test conditions, and force analysis was conducted at various RPMs, including 700, 900, and 1100. These different RPMs were recorded for further analysis.

The investigation on the hole quality of Inconel 718 in drilling operation using LN_2 as a coolant and dry conditions showed some interesting results. The study found that the use of LN2 as a coolant resulted in improved hole quality compared to dry conditions, including better surface finish and dimensional accuracy. This is likely due to the reduced thermal damage to the workpiece during the drilling process, which helped to minimize deformation and improve the overall quality of the drilled hole. It can be observed that as the drilling speed increases, the force required to drill the hole also increases. When using liquid nitrogen as a coolant, the force required to drill the hole is higher compared to the dry condition. It can be observed that the maximum force value during the process also increases as the drilling speed increases, indicating that higher drilling speeds require more force to cut through the material.

SEM images of drilled hole under dry conditions shows more signs of thermal damage, such as microcracks, due to the heat generated during the machining process. On the other hand, SEM images of drilled hole under liquid nitrogen as coolant conditions shows a smoother surface with less thermal damage. From the results of EDS Analysis it can be concluded that drilling at a higher speed without coolant leads to a reduction in nickel percentage in the Inconel 718 alloy, but the retention of iron and chromium at high levels suggests that the material still retains its strength and corrosion resistance. On the other hand, using liquid nitrogen as a coolant at higher drilling speed did not significantly alter the chemical composition of the alloy, and it retained its original properties. Therefore, using liquid nitrogen as a coolant can be a suitable alternative to dry drilling at high speeds without compromising the chemical composition and properties of the Inconel 718 alloy.

CHAPTER 6

REFERENCES

[1]ThrinadhJadam, Saurav Datta, Manoj Masanta,Wear morphology of microwave post-treated WC-Co tool during machining of Inconel 718 superalloy,Materials Today: Proceedings,Volume 38, Part 5,2021

[2]Kumar S, Satapathy B, Pradhan D, Mahobia G S. Effect of surface modification on the hot corrosion resistance of Inconel 718 at 700°C,Materials Research Express, 2019

[3]Octavio Pereira, Ainhoa Celaya, GorkaUrbikaín, Adrián Rodríguez, Asier Fernández-Valdivielso, L. Noberto López de Lacalle,CO2 cryogenic milling of Inconel 718: cutting forces and tool wear,Journal of Materials Research and Technology,Volume 9, Issue 4,2020

[4]Uma Maheshwera Reddy Paturi, Vidhya Darshini B., N.S. Reddy,Progress of machinability on the machining of Inconel 718: A comprehensive review on the perception of cleaner machining,Cleaner Engineering and Technology,Volume 5,2021

[5]Luka Sterle, Dinesh Mallipeddi, Peter Krajnik, FranciPušavec,The influence of single-channel liquid CO2 and MQL delivery on surface integrity in machining of Inconel 718,Procedia CIRP,Volume 87,2020

[6]Jay Airao, Navneet Khanna, Chandrakant K. Nirala,Tool wear reduction in machining Inconel 718 by using novel sustainable cryo-lubrication techniques,Tribology International,Volume 175,2022

[7]Navneet Khanna, Chetan Agrawal, Manu Dogra, Catalin Iulian Pruncu,Evaluation of tool wear, energy consumption, and surface roughness during turning of inconel 718 using sustainable machining technique,Journal of Materials Research and Technology,Volume 9, Issue 3,2020

[8]Shailendra Kumar Bohidar, RavitejaSurakasi, M.S. Karuna, KedriJanardhana, S. Louies Praveen, Puneet Narayan,Sustainable manufacturing for turning of Inconel 718 using uncoated carbide inserts,Materials Today: Proceedings,Volume 66, Part 3,2022

[9]Bouzakis KD, Michailidis N, Skordaris G, Bouzakis E, Biermann D, M'Saoubi R.Cutting with coated tools: coating technologies, characterization methods andperformance optimization. CIRP Ann—Manuf Technol 2012

[10]Behera B C, Alemayehu H, Ghosh S, and Rao P V. A comparative study of recent lubri-coolant strategies for turning of Ni-based superalloy. Journal of Manufacturing Processes 2017

[11]Prassan Shah, Navneet Khanna, Amit Arora, Nishkarsh Srivastava, Comparison of LN2 and LCO2 based on machining performance indicators for drilling Inconel 718, Journal of Manufacturing Processes, Volume 81, 2022

[12]A. Iturbe, E. Hormaetxe, A. Garay, P.J. Arrazola,Surface Integrity Analysis when Machining Inconel 718 with Conventional and Cryogenic Cooling, Procedia CIRP, Volume 45,2016

[13]FranciPusavec, Ashish Deshpande, Shu Yang, Rachid M'Saoubi, JanezKopac, Oscar Wlliam Dillon, I.S. Jawahir,Sustainable machining of high temperature Nickel alloy – Inconel 718: part 2 – chip breakability and optimization,Journal of Cleaner Production,Volume 87,2015

[14]Hongbo D, Gaochao W. Effect of deformation process on super plasticity of Inconel 718 alloy. Rare Metal Materials and Engineering 2015

[15]Alborz Shokrani, Vimal Dhokia, Stephen T. Newman,Hybrid Cooling and Lubricating Technology for CNC Milling of Inconel 718 Nickel Alloy,Procedia Manufacturing,Volume 11,2017

[16]F. Pusavec, H. Hamdi, J. Kopac, I.S. Jawahir,Surface integrity in cryogenic machining of nickel based alloy—Inconel 718,Journal of Materials Processing Technology,Volume 211, Issue 4,2011

[17]Thakur A, Gangopadhyay S. State of the art in surface integrity in machining of nickel-based super alloys. IJMTM 2016

[18]Aditya Kumar Sahoo, Siddharth Jeet, Dilip Kumar Bagal, Abhishek Barua, Ajit Kumar Pattanaik, Niranjan Behera,Parametric optimization of CNC-drilling of Inconel 718 with cryogenically treated drill-bit using Taguchi-Whale optimization algorithm,Materials Today: Proceedings,Volume 50, Part 5,2022

[19]Mohd Danish, Munish Kumar Gupta, Saeed Rubaiee, Anas Ahmed, Murat Sarıkaya, Grzegorz M. Krolczyk,Environmental, technological and economical aspects of cryogenic assisted hard machining operation of inconel 718: A step towards green manufacturing,Journal of Cleaner Production,Volume 337,2022

[20]Shokrani, V. Dhokia, S.T. Newman, R. Imani-Asrai,An Initial Study of the Effect of Using Liquid Nitrogen Coolant on the Surface Roughness of Inconel 718 Nickel-Based Alloy in CNC Milling,ProcediaCIRP,Volume 3,2012

[21]A.H. Musfirah, J.A. Ghani, C.H. Che Haron, Tool wear and surface integrity of inconel 718 in dry and cryogenic coolant at high cutting speed, Wear,Volumes 376–377, Part A,2017

[22]NecatiUçak, AdemÇiçek, The effects of cutting conditions on cutting temperature and hole quality in drilling of Inconel 718 using solid carbide drills, Journal of Manufacturing Processes, Volume 31,2018

[23]Sana Chaabani, Pedro José Arrazola, YessineAyed, AitorMadariaga, Albert Tidu, Guénaël Germain, Surface Integrity When Machining Inconel 718 Using Conventional Lubrication and Carbon Dioxide Coolant, Procedia Manufacturing, Volume 47, 2020

[24]Navneet Khanna, Chetan Agrawal, Munish Kumar Gupta, Qinghua Song,Tool wear and hole quality evaluation in cryogenic Drilling of Inconel 718 superalloy, Tribology International,Volume 143,2020

[25]M. Gueli, J. Ma, N. Cococcetta, D. Pearl, M.P. Jahan,Experimental investigation into tool wear, cutting forces, and resulting surface finish during dry and flood coolant slot milling of Inconel 718,Procedia Manufacturing, Volume 53,2021

[26]Ivan Sunit Rout, P. Pal Pandian, Anil Raj,Experimental study of response parameters during machining of Inconel 718 with cryogenically treated ceramic round tool using cutting fluid,Materials Today: Proceedings,Volume 47, Part 14,2021

[27]Andrea De Bartolomeis, Stephen T. Newman, I.S. Jawahir, Dirk Biermann, Alborz Shokrani,Future research directions in the machining of Inconel 718,Journal of Materials Processing Technology,Volume 297,2021

[28]EminSalur,Understandings the tribological mechanism of Inconel 718 alloy machined under different cooling/lubrication conditions, Tribology International,Volume 174,2022

[29] Prassan Shah, Prathamesh Bhat, Navneet Khanna,Life cycle assessment of drilling Inconel 718 using cryogenic cutting fluids while considering sustainability parameters, Sustainable Energy Technologies and Assessments,Volume 43,2021

[30] Mohd Danish, KubilayAslantas, Ahmet Hascelik, Saeed Rubaiee, Munish Kumar Gupta, Mehmet Bayram Yildirim, Anas Ahmed, Abdullah Bin Mahfouz,An experimental investigations on effects of cooling/lubrication conditions in micro milling of additively manufactured Inconel 718,Tribology International,Volume 173,2022

[31]Shokrani A, Dhokia V, Newman ST, Imani-Asrai R. An initial study of the effectof using liquid nitrogen coolant on the surface roughness of Inconel 718 nickel-based alloy in CNC milling. Procedia CIRP 2012

[33]Pervaiz S, Rashid A, Deiab I, Nicolescu M. Influence of tool materials on machinability of titanium- and nickel-based alloys: a review. Mater Manuf Process2014

[34]Pusavec F, Hamdi H, Kopac J, Jawahir I S. Surface integrity in cryogenic machining of nickel based alloy inconel 718. Journal of Materials Processing Technology 2011

[35]S.Ravi,M.P.Kumar, Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel,Cryogenics51, 2011