INVESTIGATION OF MACHINING INDUCED TRIBOLOGICAL CHARACTERISTICS OF INCONEL601 NICKEL BASED SUPERALLOY

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I certify that in my opinion the thesis submitted by Yasir ABBAS titled "INVESTIGATION ON MACHINING INDUCED TRIBOLOGICAL CHARACTERISTIC OF INCONEL601 NICKEL BASED SUPERALLOY" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

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"I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well."

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ABSTRACT

M. Sc. Thesis

INVESTIGATION OF MACHINING INDUCED TRIBOLOGICAL CHARACTERISTICS OF INCONEL601 NICKEL BASED SUPERALLOY

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Nickel alloys are very hard-to-cut materials and due to their strong resistance to heat and oxidation, they are widely used in several industrial sectors, especially in the aerospace industry. The study in hand tends to focus on the tribological properties of Inconel 601 under different machining environment conditions such as dry, MQL, nano-MQL, and cryo. Surface roughness quality, power consumption, tool wear, and optical microscopic images of the cutting inserts were examined by providing cutting speeds of 60,80, and 100m/min, and feed rates of 0.08 and 0.12 mm/rev. The results of the experiments have shown that the smallest value of tool wear i.e., 92µm takes place in cryo cooling conditions. Similarly, the lowest value of surface roughness i.e., 0.37µm is observed in cryo. While the least total power consumption i.e., 1660W took place in cryo cooling.

The least power consumption with the smallest tool wear along with better surface quality for Inconel 601 was achieved under cryo environment machining conditions.

Key Words : Inconel 601 Nickel based superalloys, tool wear, surface integrity, minimum quantity lubrication (MQL), Cryogenic cutting, nano-MQL, sustainability, power consumption

Science Code : 91438

ÖZET

Yüksek Lisans Tezi

INCONEL601 NİKEL BAZLI SÜPERALAŞIMIN TALAŞLI İMALAT KAYNAKLI TRİBOLOJİK ÖZELLİKLERİNİN İNCELENMESİ

Yasir ABBAS

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
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Nikel alaşımları, kesilmesi çok zor malzemelerdir ve ısıya ve oksidasyona karşı güçlü dirençleri nedeniyle, özellikle havacılık endüstrisi olmak üzere birçok endüstriyel sektörde yaygın olarak kullanılmaktadır. Eldeki çalışma, Inconel 601'in kuru, MQL, nano-MQL ve Kriyojenik gibi farklı işleme ortamı koşulları altında tribolojik özelliklerine odaklanma eğilimindedir. Kesici uçların yüzey pürüzlülük kalitesi, güç tüketimi, takım aşınması ve optik mikroskobik görüntüleri, 60,80 ve 100m/dak kesme hızları ve 0,08 ve 0,12 mm/dev ilerleme hızları sağlanarak incelenmiştir. Deneylerin sonuçları, en küçük takım aşınma değerinin yani 92µm'nin Kriyojenik soğutma koşullarında gerçekleştiğini göstermiştir. Benzer şekilde, en düşük yüzey pürüzlülüğü değeri yani 0.37µm Kriyojenik gözlenir. En az toplam güç tüketimi yani 1660W ise kriyo soğutmada gerçekleşmiştir.

Inconel 601 için daha iyi yüzey kalitesi ve en küçük takım aşınması ile en az güç tüketimi, Kriyojenik ortam işleme koşullarında elde edildi.

Anahtar Kelimeler : Inconel 601 Nikel bazlı süper alaşımlar, takım aşınması, yüzey bütünlüğü, minimum miktarda yağlama (MQL), Kriyojenik kesme, nano-MQL, sürdürülebilirlik, güç tüketimi.

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CONTENTS

Page

Page

Page

LIST OF FIGURES

Page

Page

LIST OF TABLES

Page

SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

F_t : Tangential force

F_n : Normal load

μ : Friction coefficient

F_d : Asperities deformation

F_a : Adhesive friction

f_t : Frictional force

L : Sliding total distance

K : Coefficient of wear

H : Hardness of softer materials

w_w : Wear width

w_d : Wear depth

s : Sliding distance (mm)

N : Newton

mm : Millimeter

μm : Micro-meter

ABBREVITIONS

SEM	: Scanning electron microscopy
Al	: Aluminum
N2	: Liquid nitrogen
Ti	: Titanium
CNC	: Computer numerical control
TO	: Thermal oxidation
Cryo	: Cryogenic
BUE	: Built Up Edges
CFRP	: Carbon Fiber Reinforced Polymer
TiC	: Titanium Carbide
Ti6Al4V	: alpha-beta titanium alloy
MQL	: Minimum quantity lubricating

PART 1

INTRODUCTION OF NICKEL BASED ALLOYS

1.1 NICKEL BASED ALLOYS

Nickel is a transition metal with an atomic number of 28 and is found in the periodic table's fourth period/row. Nickel is a silvery white metal which is malleable, hard, and ductile. It is a good thermal and electrical conductor having a melting point of 1453 Celsius and a boiling point of 2913 Celsius. During service at high temperatures, nickel-based superalloys typically combine excellent strength and corrosion resistance. Initially, they were inspired and propelled forward by the realization that increasing the combustion temperature and/or pressure may improve the efficiency of thermal power production devices. As a result, they have been enormously used in combustion engines, such as aircraft gas turbines, as well as power generation in nuclear, thermal, and fossil fuel power plants. Components of the engine like rotors, blades, turbine discs, spindles, bearings, and bolts, as well as jackets for steam and stationary gas turbines are usually nickel-based components in the energy industry. Most spinning turbine parts, as well as casings, linkages, and some engine mounts, are commonly built of high-performance nickel-based superalloys in the aircraft sector [1].

1.2 PROBLEMS IN MACHINING OF NICKEL-BASED ALLOYS

- they can be more expensive
- processes like smelting and machining become complicated and difficult because Nickel-based superalloys have a large amount of a strengthening element, such as Mo, Ti or Nb.
- rates of tool wear are high in Nickel alloys that’s why Abrasive machining is challenging, high cutting energy is needed for machining of Nickel-alloys

- enormous heat generation is challenging
- metallurgical microstructures of these materials are degraded because of machining
- Their elevated capability causes great deduced energy which raises the surface temperature
- low thermal diffusivity is a difficulty in conducting away excessive heat
- poor grindability
- cause crucial chip loading due to adhering to grains [2]

1.3 METHODS TO IMPROVE MACHINING OF NICKEL-BASED ALLOYS

A material's machinability can be defined as a mix of low cutting force, high metal removal rate, improved surface finish/integrity, extended tool life, well broken chips, and uniform dimensional precision.

- machining procedures
- workpiece properties
- cutting conditions
- tool properties
- machine tool - tool workpiece dynamics are some of the elements that influence a material's machinability.

Standard techniques make INCONEL alloy 601 easy to manufacture, machine, and weld. In all service situations, welding solutions are accessible. INCONEL alloy 601 should be cleaned before being heated, same as other high-nickel alloys. Before a heating operation, any external substances such as paint, oil, grease, and workshop soil must be excluded from the material. The alloy must be heated in a Sulphur-free environment. Sulphur-free fuels must be used for open heating. The furnace environment should also be somewhat lower to avoid excessive oxidation of the material. Heat treatment does not strengthen INCONEL alloy 601. However, by combining cold work and annealing procedures, the alloy can reach a wide range of strength and hardness. When determining an annealing technique, the amount of work and the material's size must be considered.

Nickel alloys are categorized in different groups according to their machinability behavior, as the below figures shows the increasing mechanical properties and resultant machining difficulty of all the groups [3].

During machining nickel alloys following facts should be kept in mind:

- A nickel alloy's hardness increases faster than that of most other metals when it is physically worked. The alloy's hardness is swiftly increased by the combination of high heat generation and physical exertion, leading tools to dull and fail quickly. Parts may be trashed, and tools may be broken because of this [4].
- Chips tend to grow stringy and attach themselves to a tool's cutting edge as nickel alloys are machined and heat is created. Built up edge, or BUE, causes the tool's cutting edge to round, resulting in poor cuts and higher friction, which contributes to work hardening [5].
- As the cutting forces involved in the cut rise, the built-up edge accelerates tool wear. A blunt tool is being driven into the workpiece now that the cutting edge has been rounded by welded chips. Rather than cutting through the metal, the tool pushes it, resulting in inferior cuts and greater friction [6].
- When a tool's internal heat builds due to poor cutting, thermal cracking can occur, which is defined by fractures that form perpendicular to the cutting edge. Extreme internal tool temperature changes cause fractures within the tool.
- When a cutting tool overheats rapidly while cutting nickel alloys, cracks can occur, resulting in calamitous tool fiasco. Galling, which is categorized by portions of the tool falling off due to the same adherence that causes BUE, can also occur at high temperatures.
- Pieces of the tool may break off as it is welded to the workpiece and the machine continues to rotate it, resulting in tool failure.

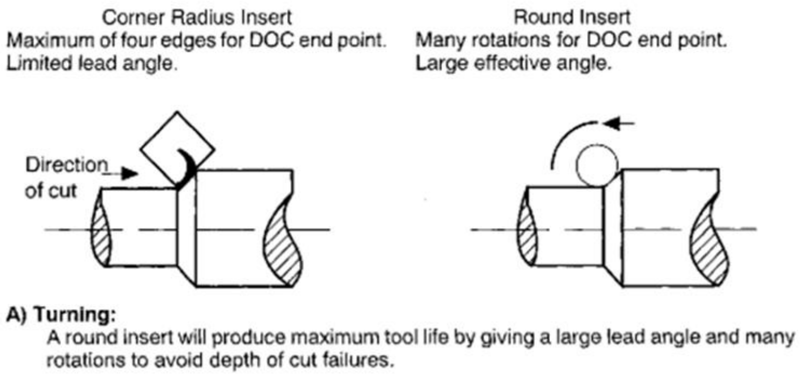


Figure 1.1 Types of tool insert used in Turning operation [7].

To process nickel alloys effectively, the first step is to maintain temperatures under control while the workpiece is being cut. It is required to use a high-pressure coolant. The coolant stress needs to be at least 1000 psi. This high pressure concentrated on the workpiece's cutting zone dissipates heat in both the cutting tool and the workpiece. Hence, the possibilities of work hardening are reduced. Because of its environmentally favorable properties, Minimal Quantity Lubrication has been regarded as an effective near-dry technique in order to make the machining process more environmentally friendly.

The use of a high-pressure coolant will also help eliminate chips from the cutting region. BUE is caused by those spicy gummy snacks. The possibility of BUE forming on the cutting edge is reduced by removing them as soon as feasible. Chip removal is also necessary to avoid chip recutting [8].

Figure 1.2 Cooling Fluid [9].

Chips absorb a lot of heat and often harden as a result. Cutting these hardened chips again can decline the cutting edge, which results in inferior cuts and a shorter tool life. Water-based cutting fluids are preferred in general because they have faster heat removal rates and a lower viscosity, both of which are important for high metal removal operations [10].

Wherever practical, use climb milling processes to help with heat removal. When climb milling, the wideness of the chip is highest at the start of the cut and gradually decreases until the cut is completed. Because the cutting tool does not brush against the workpiece, less heat is created. Maximum of the heat formed by the incision is passed to the chip [11].

INCONEL alloy 601 cannot be bright annealed in a typical industrial furnace due to its aluminum and chromium concentration, which causes it to create a refractory surface oxide when heated. Pickling is frequently necessary to achieve brilliant surfaces on hot objects. Because of its inherent resistance to chemical degradation, alloy 601 needs specialized pickling methods.

The nitric/hydrofluoric acid solution can generally remove the material's light oxide which has been toughened and chilled from contact with air, such as in hydrogen. The pickling method should be used to remove heavy oxide, such as those produced by hot-working operations.

At temperatures ranging between (650-870°C), the alloy has low ductility and should not be worked in that range. To develop high tensile characteristics, light working at temperatures below (650°C) can be done.

1.4 PURPOSE AND SCOPE OF WORK

The purpose of this research is:

- To evaluate the methodology and optimal parameters for increasing the sustainability performance during the turning process of Inconel 601 as a workpiece material.

- To investigate the machinability of Inconel under following sustainable machining processes which consist of dry turning, Minimum Quantity Lubrication (MQL), nano-MQL and Cryogenic cooling conditions.
- The process is performed at altered levels of cutting speed, depth of the cut and feed. Full factorial method is employed for investigation of optimal parameters of this process
- The machining fragments will be observed for surface integrity, total power consumption and tool wear.
- The aim of the research is to optimize machining factors for the workpiece material which is Inconel 601 and compare results of dry cutting to the study of effects of a lubricant (MQL) in a cutting procedure as well as to the effects of nano-MQL and cryogenic cooling.

1.5 PROBLEM STATEMENT

Due to the presence of strengthening element, such as Mo, Ti or Nb in the nickel-based alloys, it shows poor tribological behavior such as:

- Surface roughness.
- High Tool wear.
- High heat generation during machining.

1.6 RESEARCH QUESTIONS

- Can addition of nano powder to MQL lubrication and cryo conditions lead to a smoother surface roughness compared to other machining environment situations?
- Is carbide turning tool suitable for cutting Inconel 601 alloy?
- What is the wear condition of carbides inserts under several input machining parameters?
- Under which cutting conditions, INCONEL 601is more efficient, dry, MQL, nano-MQL or cryogenic?

1.7 SIGNIFICANCE OF THE RESEARCH

Inconel601 has a higher tensile strength than stainless steel and maintains that strength even at higher operating temperatures. In comparison to stainless steel the melting point of Inconel is lower, it has a higher operating temperature limit. The reason is that at high temperatures, Inconel is much stronger than stainless steel, while being more resistant to scaling and oxidation too. It is extensively used in aerospace, power production, thermal processing, chemical treatment, and land-based gas turbine engines. Due to these benefits, it is widely in the aerospace industry such as manufacturing of blades and containment rings in gas turbines, jet-engine igniters, seals and combustors diffuser, assemblies, and combustion-can liners.

It is one of the demanding factors to make manufacturing process of Nickel alloys more cost-effective environment friendly, with less wear of tool and to achieve better surface quality. Due to wide application of Inconel 601, it is crucial to optimize the machining the machining parameters and to research best suitable machining environment for achieving best tribological properties. Further in terms of sustainability, machining process is an important manufacturing process that subsidizes worldwide economic development[12]. On the one hand, machining performance by enhanced tool material, improved higher output, and excellence, parallel to the side, environmental and health- beneficial skills are becoming progressively vital in lieu of attaining clean, improved, and nontoxic machine processing [13].

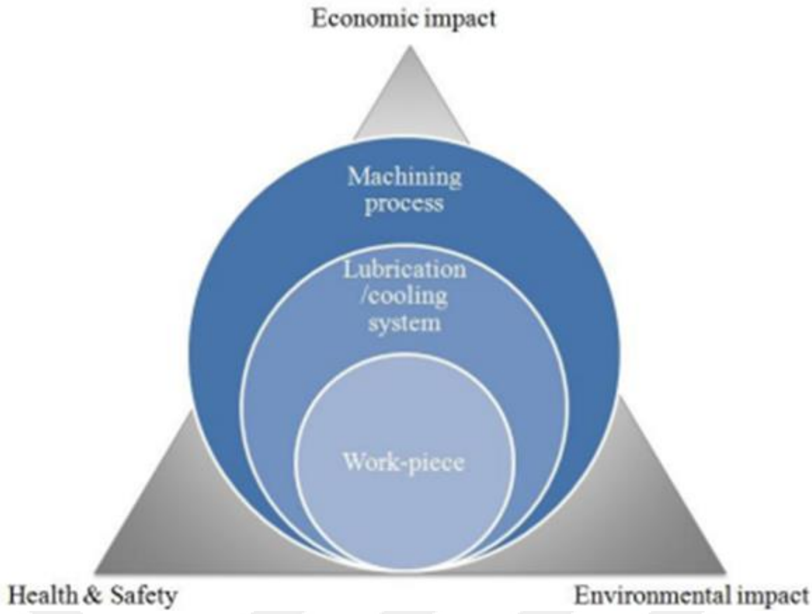


Figure 1.3 Sustainable Manufacturing [9].

Dry machining, solid lubrication, minimal quantity lubrication (MQL), gaseous cooling, cryogenic cooling, sustainable cutting solutions, and nano fluids are the main alternatives of cutting fluids [3]. Due to this reason, research on the best environmental cutting conditions along with optimal machining parameters has become a significant topic in the past decades.

1.8 ORGANIZATION OF THESIS

The study is organized in the form of chapters and sections. In this regard, the thesis consists of 6 chapters. Chapter 1 describes the reason of motivation by general description of super alloys background and further elaborates nickel alloys with respect to its industrial and commercial applications to emphasize its significance. In this perspective, challenges in machining nickel alloys were considered to determine the aim of the research. Further later, thesis organization is presented.

Chapter 2 describes the literature review of the research papers on the machining ability of nickel alloys and cooling conditions. Research gaps were also discussed.

In Chapter 3, Historical aspects of nickel alloys, their chemical characteristics and applications was discussed. Further machining and its tribological literature were also discussed.

Chapter 4 elaborates about experimental apparatus and their features, further elaborates about experiment setup and solutions which further elaborated in detail and Chapter 5 includes results and discussion of the experiment. Chapter 6 concludes thesis outcomes.

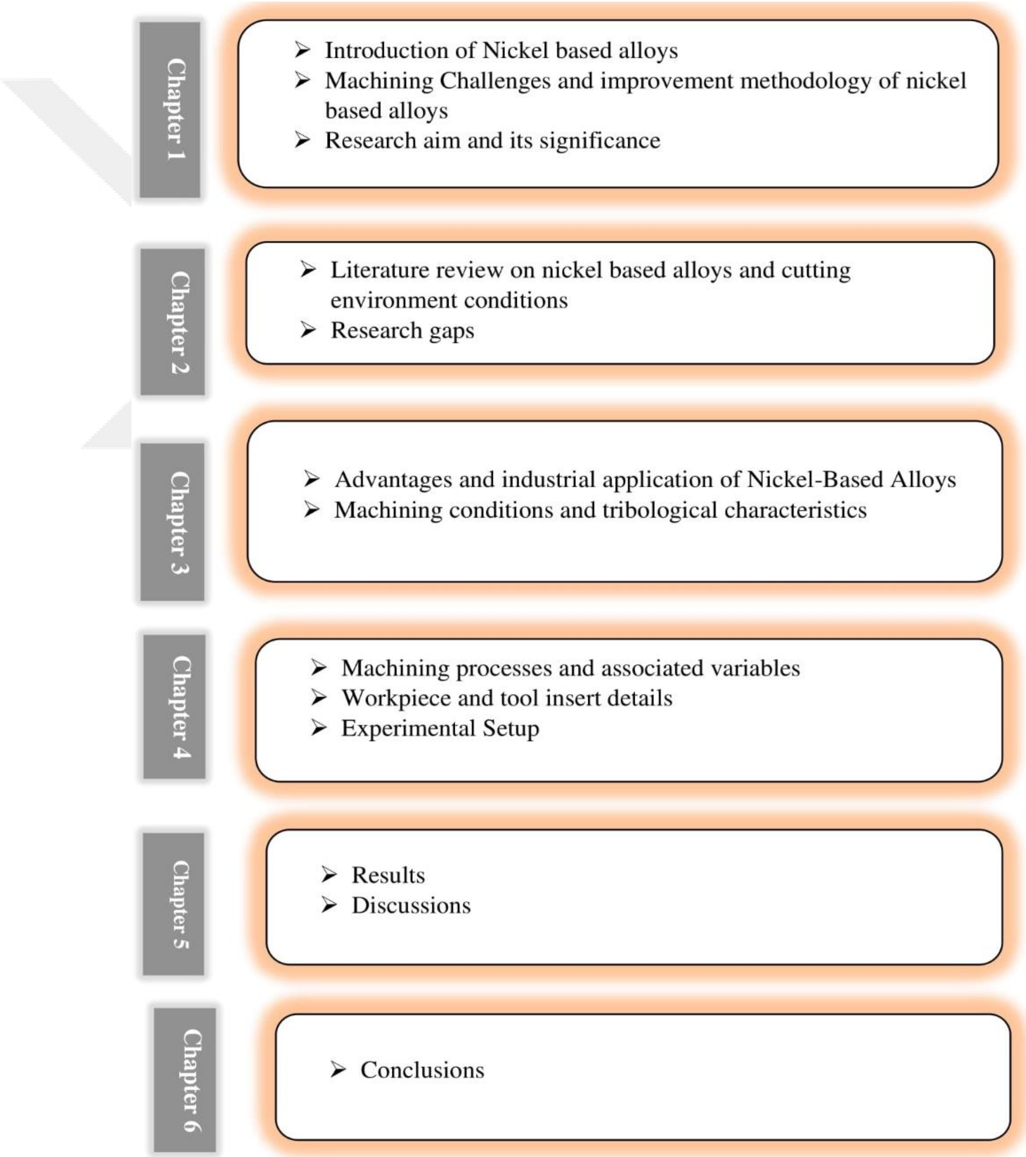


Figure 1.4 Organization of thesis.

PART 2

LITERATURE REVIEW

2.1 LITERATURE REVIEW ON NICKEL-BASED ALLOYS

Previous studies show that a few research have been conducted for finding the optimal parameters for Inconel 601 which is from the family of super alloys based on nickel. Inconel 718 is member of the same family and has some machining properties in common with Inconel 601. So, the criterion for finding their optimal parameters is somewhat the same. Hence the research based on Inconel 718 are reviewed in this regard.

Ezugwu et al. (1999) and Grguras et al. (2019) stated that Nickel-based superalloys are highly heat resistant, have excellent metallurgical stability, a high level of carburization resistance, are easily fabricated, and have superior aqueous corrosion resistance, the issue becomes more complicated when machining these materials [14]. Superalloys based on nickel are tough to cut and have high mechanical strength. For these reasons, cutting fluids are typically used to convert Ni-based superalloys

Zhu (2013) argued that one of the materials that is incredibly challenging to cut is superalloy based on nickel. The contact between the tool and the workpiece throughout the machining process; results in significant plastic deformation in the immediate zone of the workpiece and high levels of abrasion. Extreme tool wear is known as one of the core blockages that limits the machinability index of nickel-based alloys and its numbers of applications due to the cutting heat that results from the serious work hardening. Other flaws include regular tool variations, small tool life, low output, and high power intake [15].

Vukelic et al. (2020) found after experimentation that if all necessary actions and arrangements can be completed deprived of the usage of cutting fluid, dry machining is particularly advantageous. This can be accomplished by choosing the right machine tools, good fixtures, and best cutting tools while cautiously taking into account the features of the workpiece. It is necessary to use solid fixtures that offer dependable workpiece locating and clamping, along with high-accuracy machine tools, high-power. It is also anticipated to use cutting tools which are coated with suitable geometry [1].

Thakur (2016) machined Incoloy 825 and to elude or diminish the need of cutting fluid, especially when machining challenging to cut nickel-based alloys, studied the viability of TiN or TiAlN multi layers coated tools in dry machining conditions. Using cutting fluid has been more successful in lowering temperature of cutting zone. Under finish mode, MQL in special produced the lowest cutting temperature possible, whereas depending roughing method, there was practically any variance in the outcome [16].

Kamata and Obikawa (2007) did experiments in which three distinct kinds of coated carbide tools were used to finish-turn Inconel 718, a nickel-based superalloy, using minimal quantity lubrication (MQL). Cutting speeds were raised to significantly higher levels, and the TiCN or Al2O3 or TiN covering performed best in MQL conditions of cutting, followed by the TiN or AlN super lattice coating. TiCN or Al2O3 or TiN coating in damp cutting had the extended tool life, however the surface texture was subpar. The finish turning of Inconel 718 with MQL was determined to have the best air pressure life. Additionally, it was discovered in an research utilizing Argon as an oil mist carrier gas that the MQL carrier gas is crucial for cooling the cutting point [17].

Shinozuka et al. (2006) performed grooving of 0.45 percent carbon having steel with a carbide tool under coating of triple layers of TiC/TiCN/TiN which allowed researchers to assess the effectiveness of minimal quantity lubrication during high-speed cutting. When cutting on high speeds such as 4 and 5 m/s, this technique; MQL with vegetable oil supply decreased flank and corner wears more efficiently than using a cutting solution (7 ml/h). When the air supply pressure was increased during MQL grooving, the wears dramatically declined. This indicated that the oil mist over was transported to the boundary between the flank wear and machining surface primarily by the air supply [18].

Makhesana et al. (2021) developed an experimental setup for Inconel 718 machining: minimum quantity lubrication having solid lubricant. In assistance of MQL, dry or flood cooling, and solid lubricant (MoS2 and graphite), Surface roughness, chip morphology, tool wear, and micro hardness of the machining surface were considered while evaluating the effects of these procedures. In comparison to alternative machining settings, experimental results showed that MQL using molybdenum disulfide was successful in improving tool life and surface polish. By enhancing surface finish and tool life when combined with MQL in comparison to chosen machining settings, the results further highlighted the efficiency of PVD coating [19].

Yazid et al. (2007) explored the outcome of machining conditions and cutting parameters on surface quality during turning of Inconel718, which has a high corrosive resistance, nickel based super alloy, under the given three cutting conditions. Typical surface roughness readings for these conditions during the studies were examined [20]. Although it's not quite clear from the results, values of surface roughness were marginally greater. So, the surface roughness tends to be rather harsh toward the completion of tool life due to deformation on the flank face or formation of buildup edges, which is frequent when milling Inconel718, even though the obtained values were quite constant [20].

Agarski et al. (2020) used three turning insertions which were coated with TiAlN AlCr2O3 by physical vapor removal to turn a workpiece made of the superalloy Inconel 601 dry in the longitudinal direction. Calculations were made for machining times, power requirements, and energy usage. For average roughness, tool wear, and power, regression models were created. According to the findings, Inconel 601 is a Ni-based superalloy that demands dry turning with larger turning insert radii, faster cutting speeds, and lower feeds and depths of cut. It enables for required workpiece surface quality and satisfactory flank wear of the turning insertion while dramatically lowering cutting time, energy use, and adverse environmental effects [1].

Shalaby and Veldhuis (2019) examined how chip development and tool wear occurred during dry finish turning of Inconel718 super alloy. At different cutting speeds, with addition of pure alumina and ZrO2 and alumina matrix strengthened with silicon carbide whiskers apparatuses were employed. SEM analysis of chip cross sections and undersides was done to learn more about the process of chip formation. Due to its superior resistance for coarse wear and the production of a protective tribo layer sapphire at the tool chip border under difficult cutting circumstances, pure alumina with addition of ZrO2 was found to be a suitable alternative for milling Inconel 718. For this tool material, it was discovered that fragmenting and notching of the cutting edge decreased with a rise in cutting speed [21].

Yildirim et al. (2020) argued that although Nickel based superalloy 625 finds many applications in aeronautical industries due to its high resistance of temperature and oxidation and good weldability but it is hard to machine and during dry machining of this metal tool wear is prominent and chip formation rate is too high and the process becomes very complicated due to production of excessive amount of heat. So, the researchers look for other alternative techniques like MQL, cryogenic or hybrid cooling which are more sustainable methods. The influence of minimum quality lubrication or cryogenic cooling with liquid nitrogen was examined on various output machining parameters such as surface roughness, tool wear, cutting temperature and chip formation etc. the tests were conducted at three different turning speeds and the results showed that hybrid cooling technique improves the surface integrity, decreases the tool wear to a large extent consequently increasing the tool life. The chip formed during the operation was also improved in texture because of these conditions [22].

Chetan et al. (2019) argued about the health and environmental hazards related to cooling fluids used in machining procedures. Their experiment results proved that cryogenic cooling is more sustainable in turning of Nickel based alloy called Nimonic 90 which otherwise is very difficult to machine in dry conditions and in MQL causes health and pollution risks. The output parameters for all the conditions were compared and when liquid nitrogen was applied as a coolant, the flank wear reduced to a great extent. The formation of the groove during the turning operation is avoided by cryogenic cooling and other limitations which are prominent in dry cutting are reduced by this technique. According to them the feed rate is the most important factor in increasing the cutting force. Liquid nitrogen assists in avoiding notch formation and fracture, hence cryogenic cooling is the best method for machining of Nimonic90 [23].

Saleem and Mehmood (2022) examined the spraying of vegetable oil during orthogonal cutting of Nickel based alloy Inconel 718. During the experiment two vegetable oils, castor oil and sunflower oil were used for spraying as a coolant and Taguchi approach was applied for analysis of findings. The tests were conducted at three different cutting speeds, pressure of air and feed rates by keeping the cut depth same. The main output parameters like surface integrity, roughness and tool wear were evaluated and the findings revealed that surface roughness is completely dependent on feed rate as it has a great influence on the surface integrity. The optimal parameters for this type of cooling were compared to that of dry machining and it was evident that this technique was far better than the dry process and the performance of tool material is very much improved by this. Tool wear and surface roughness measured in these experiments were minimum proving this technique as a good alternative to increase tool life [24].

Sirin et al. (2021) proposed that ceramics tool pieces should be used for cutting of X-750 because these alloys, despite their high resistance and thermal properties, are very difficult to machine when carbide tools are used. In the experiments, the researchers used different cooling conditions including dry, cryogenic, base fluid MQL and nano fluid MQL and their influences were studied on machining parameters such as flank wear, cutting force, cutting temperatures, microhardness, and surface roughness. The surface roughness was improved to a great degree when base fluid MQL was used and similarly with the use of nanofluid MQL, the surface integrity was much better as compared to dry machining processes. However, the tool wear was less in dry machining for ceramics tools than nanofluid and base fluid MQL. The cutting temperature and forces were also reduced by using this technique and microhardness started to increase with changing conditions [25].

According to Tu et al. (2022) Nickel based alloys have poor machinability, but their other mechanical properties made them a best fit for use in aerospace applications. The experiments were performed on Nickel based alloys by providing different cutting speeds to examine the impact of speed on tool wear and to evaluate the reason why ceramic tools like SiAlON fail during the dry machining process. The tools were subjected to high-speed turning processes and tool wear and its improvement were examined at different speeds. The experiment results show that when cutting speed is low, chipping and strain hardening effects are prominent which increase the tool wear rate and decreasing tool life and at higher cutting speed there is intense adhesion in the tool and chip and fracture. So, knowing the optimal cutting speed is important for efficient machining of ceramic tools using Nickel based alloys [26].

Singh et al. (2022) presented the sustainable method of machining Nickel alloys and according to them, when coated tools are used in dry machining, the procedure is more efficient than using uncoated tools. To prevent the sticking of chips to tool material and workpiece, to reduce the amount of tool wear and to increase tool life, lubrication is necessary so that the friction between tool and workpiece is minimum. Using vegetable oil in minimum quantity lubrication is also helpful in reducing surface roughness and tool wear. Cryogenic cooling along with liquid nitrogen assists in cutting of metals that are difficult to machine and the described process is sustainable also in terms of environmental and health aspects. And when coated tools are used for machining of Nimonic 263 alloy, the process becomes more and more efficient. Hance, the results prove that cryogenic and MQL are both sustainable and improve tool life [27].

Bertolini et al. (2021) argued that Inconel 718 is a difficult to machine metal because of the excessive amount of heat which is generated during the process. To solve this problem flooding is done but this technique is not sustainable as it has some environmental and health hazards so, MQL is the best method for machining of such metals. When nanoparticles are added to the vegetable oil which is sprayed during machining, the procedure is known as hybrid cooling and graphene nanoplatelets are added to this nanofluid mixture. Tool wear at different points was examined and surface integrity was also measured. However, tool wear mechanisms such as adhesion and abrasion were also identified. When the rate of flow of nanofluids is highest, the tool wear will be the lowest, hence the machinability and sustainability are increased [28].

Marques et al. (2019) studied the effect of adding a solid lubricant in the spraying oil during MQL in the turning operation of Inconel 718. Machining output parameters like surface integrity, tool wear, cutting temperatures and cutting forces were examined. It was also noted that during the process if MoS2 is added, the tool wear is less and the tool life is improved, surface integrity also becomes better and the components of cutting forces also have the lowest values. The tool life is increased to a greater degree as compared to dry machining and addition of solid lubricant also had a positive effect on tool life. Such cutting fluids are an efficient source of easy machining of ceramic tools which are otherwise difficult to cut. The prominent tool wear was notch during the experiments [29].

Ramana et al. (2021) found an environmentally, economically, and healthy sustainable process for machining of superalloys. They examined the performance of Nickel alloy A286 which contains iron in both coated and uncoated form during the dry machining process. The experiments were conducted to evaluate the influence of several machining parameters like flank wear, surface integrity and roughness, cutting speed and temperature, tool wear and chip morphology on the machinability of the tool material. The coated alloys' findings were compared to those of uncoated alloy. The results revealed that coated tools improved the rate of tool wear and surface roughness to a better degree and these parameters depend greatly on the feed rate. In case of the uncoated tool, the flank wear is dependent on the depth of the cut while in coated tool the wear largely depends on the cutting speed [30].

2.2 LITERATURE REVIEW ON COOLING CONDITIONS

Sterle et al. (2020) proposed that liquid carbon dioxide can be utilized as an option for flood cooling or lubrication in the machining process. They investigated the impact of this type of lubrication in which LCO2 was mixed with other lubricants on the surface roughness of the tool and workpiece material while machining basically milling Inconel 718. Other characteristics such as microstructure, surface topography and surface integrity were measured in all the cooling conditions and carried up to five experiments using different conditions. They found out that when LCO2 is not lubricated with any other MQL oil or MSo2, the surface remains clean, and the result is fantastically improved by using MSo2. Average surface roughness is less when LCO2 and MSo2 are used as compared to flood lubrication. When the lubrication is not enough, it causes smearing of material alongside the feed. The degree of layer deformation is the same and independent of the cooling condition [31].

Khan et al. (2022) considered hybrid-lubri cooling processes as an alternative for the machining of hard metals especially Nickel based alloys to minimize the consumption of electrical energy and to increase the rate of production and profit. In this regard they examined the advanced process of cryo MQL and a flood lubrication was also used to measure the pre-set performance parameters such as consumption of electrical energy, specific cutting energy and power consumption. They performed two series of experiments provided the same conditions and the results were systematically developed, arranged, and compared. They found out that Cryo MQL is the best technique so far to get the best results i.e., low cutting energy. Less consumption of power and energy etc. during the process if cutting conditions are kept low, the economic sustainability becomes poor which indicated that this technique is economically sustainable but not environmentally [32].

Rodriguez et al. (2020) proposed that the metalworking fluids used in the machining process are very risky for health and environment yet also very important in the grinding procedures to control the excessive formation of heat and to prevent the roughness of surface. According to them MQL can be used as an alternative instead of the flood lubrication. But they also considered an important limitation of this process which is the chip formation during the process that clogs the machine wheel and hence the lubrication action is reduced. In the experiment, WCJ technique by using one portion of oil and 5 portions of water was also examined and researchers found out that HMQL produced improved results by lowering the surface roughness, consumption of power and energy and reducing the production of carbon dioxide. It was evident from the experiment results that dilution of oil with water reduces the lubrication action but on the other hand HMQL increases this action. The clogging was also reduced to a great extent by performing HMQL [33].

Nagaraj et al. (2020) proposed that the machining of CFRP metals is a very complicated process; the drilling of such composites causes some process defects in terms of torque, the force of thrust and the diameter of drilled holes. Different cutting and cooling conditions were applied in order to investigate the optimal parameters for machining of such materials. The researchers reached the conclusion that torque, and the force of thrust are greatly affected by the cutting conditions and the results are highest by using cryogenic cooling techniques. The torque is independent of the changing feed while the thrust is improved if the feed is constantly changed. Under cryogenic environments, the holes produced by drilling are improved and better and the tool life can also be increased. Delamination can also be avoided by lowering the feed. It is evident from the results that cryogenic drilling is far better than the conventional dry drilling process and is an economically and also environmentally sustainable procedure [34].

Ross et al. (2021) considered the environmental hazards and health risks associated with cutting or cooling fluids and to look for a sustainable procedure utilizing adequate cooling and lubrication. For acquiring the optimal parameters and to reduce the consumption of energy in the machining process Nimonic-80A was machined under this technique and the results were compared to the findings of the other cooling techniques. COPRAS technique was also involved to look for optimal conditions and the final results conclude that if cutting speed is kept 60m/min and feed rate is 0.04mm/rev then the energy consumption will be controlled, and optimal values will be achieved. The hybrid strategy in which MQL and CO2 are combined is found as an effective solution for outcoming the problems related to machining of metals. Cryogenic cooling minimizes the generation of heat during machining which results in better surface integrity and is a sustainable process [35].

Jamil et al. (2022) performed the machining process using an entirely new technique in which hybrid ethanol-ester oil lubri-coolant is used to perform machining operation on titanium alloys. To optimize the thermo-physical properties along with the tribological properties, various parameters such as surface roughness, tool wear, temperature or the cutting force, the technique is used and then the results are compared to the parallel findings of dry cutting processes. The results of the experiments revealed that when the above-described coolant is used all the output parameters are lowered including less tool wear, less surface roughness, low consumption of power and energy and consequently increasing the tool life. This oil has anti-wear properties and reduces the cutting temperature to a great extent and also the roughness of the surface is minimum by using this technique [36].

Gupta et al. (2022) proposed that in cryogenic processes the cooling action is exceptional, but the lubrication action is not up to mark, and the reverse goes for MQL. The use of hybrid cooling lubricants is now more in demand. The researchers in this experiment used Blaser oil with ethanol as a cooling lubricant and compared the machinability of the materials with other cooling conditions and optimized the cooling parameters, especially tool flank wear. SEM and EDS were used to analyze the results of the experiments and the findings reveal that the tool life is increased by 66% by using this oil however tool wear is also prominent in machining titanium alloys i.e., Ti-6Al-4 V. During dry cutting an excessive amount of heat is produced and by using hybrid cooling lubricant not only the tool wear is improved but also the heat can be controlled. Tool wear is high in ambient MQL temperature while it is less when dry ice temperature in the same technique is used [32].

Grguras et al. (2021) argued that when titanium alloys especially Ti6Al4V which finds enormous applications in aeronautics and defense systems, is machined with provided dry cutting conditions causes an excessive amount of heat and different types of tool wear affecting the tool life. Flood lubrication is also not helpful for dry drilling of this metal. So, the researchers in this study were keen to apply robotic drilling by lubricating the process with LCO2 and MQL, the corresponding results were measured, analyzed, and compared to that of dry drilling. The cutting force, the thrust, torque, surface roughness and chip morphology were all studied in this technique and the findings revealed that this cooling lubrication technique intensifies the thrust force by up to 42% and hence the drilling torque is decreased by 20% by this type of cooling effect. The breaking of chip during the process is also improved by this technique [37].

Jamil et al. (2021) performed experiments using titanium alloy Ti6Al4V as the workpiece material involving MQL technique with CO2 snow and LN2, the findings were recorded by changing the cutting conditions constantly. The machining process properties like surface roughness, tool wear and the temperature provided during cutting were studied in this technique and the findings were compared to dry cutting processes. There was a great improvement not only in the machining characteristics but also the sustainability principles. The use of CO2 snow was the best for milling titanium alloys, then cryogenic cooling has a good impact on the machining process as compared to dry milling. Also, the energy efficiency reaches the highest when CO2 snow is used. The surface integrity is also improved by 53.8% by using this technique [38].

Chen et al. (2021) studied the effect of cooling conditions and the radius of cutting edge on the surface quality during the machining process. During the experiment several cooling techniques were involved including dry, MQL, cryogenic or hybrid cooling etc. Titanium alloy Ti6Al4V was orthogonally cut and various machining parameters such as cutting speed, cutting edge, cutting radius, thrust force and plastic deformation were examined. The results showed that when hybrid cooling techniques were used by keeping the cutting radius large, surface hardness also increased to some extent and the plastic deformation layer got thinner. The cutting force and its components are a little bit higher in cryogenic cooling as compared to MQL and dry cutting conditions. The curling of the chip also reduces as the radius is increased [39].

Kuram et al. (2021) proposed that cutting fluids are not completely sustainable as they cause some serious environmental and health issues. The researchers compared the machining output parameters of cryogenic and hybrid cooling with the findings of minimum quality lubrication. During the milling of titanium alloys, different conditions were applied like spray of liquid nitrogen, carbon dioxide or carbon dioxide with MQL etc and cutting speed was constantly changed to evaluate machining parameters such as cutting temperature, chip morphology, surface roughness and tool wear at different levels. It was found out that hybrid cooling not only increases the tool life but is also an environmentally and economically sustainable alternative [40].

2.3 RESEARCH GAPS

There are numerous studies which have been carried out to find optimum parameters to enhance tool life and reduce tool wear and improve surface roughness by using different cooling methods in various machining processes like drilling, turning, milling etc. The requirement of such machining activities in the industry provides researchers an opportunity to study and research the machinability of super alloys and to tackle the challenges related to it.

In recent years, the use of cooling/lubrication techniques has been essential to lowering the severe heat temperatures that result from dry cutting, safeguarding the tool's sharpness, and enhancing surface integrity [41]. However, the conventional cooling technique needs to be changed.

For sustainable machining, one of the most prominent methods are MQL, which provides efficient lubrication, and cryogenic cooling techniques, which provide excellent cooling performance [42]. Because MQL lacks cooling performance and cryogenics lacks lubricity, hybrid cooling/lubrication are a viable way to get around both approaches and drawbacks [43]. By considering the several factors such as cost, efficiency and environmental impacts, the cooling conditions are being determined.
Sustainable machining primarily offers ecologically sustainable compliance, lower machining costs, lower power usage, lower wastes, and enhanced performance in terms of employee health and safety [44]. Investigating dry and MQL machining procedures and comparing their productiveness using their ideal cutting parameters allows for the sustainable machining of nickel based super alloys under varied cutting circumstances and cooling environments [45].

A survey of the literature reveals that there are several superalloys materials grades available, optimization methods, cooling methodology and texturing process combinations available for testing such as Inconel 601. This could be the great opportunity to improve the quality benchmark and push the boundaries to create the ideal machining environment in the future.

PART 3

THEORETICAL BACKGROUND

3.1. NICKEL-BASED ALLOYS

3.1.1. Historical Aspects of Nickel Alloys

Swedish scientist Axel Cronstedt in 1751, was the main scientist to recognize and isolate Nickel as an element. It was prominent in the nineteenth century in electroplating and alloys like "nickel silver" (also known as German silver), in which it is alloyed with Cu and Zn. It was given its name because of its color; it does not include any silver. In the United States in 1857, Nickel which was alloyed with copper was first used in coins. Although the "nickel" was not made of pure nickel, but the pure nickel was used for coins in Switzerland in 1881. Early in the twentieth century, stainless steels were developed, and nickel was revealed to play a highly advantageous role in various of the typical grades, which remains to this day. Nickel based alloys were discovered to have great resistance for corrosion and the ability to endure high temperatures, identifying them ideal for chemical industries and letting the practical implementation of the jet engine [46]. Nickel's demand has risen dramatically over the last century because of these innovations which is still the case today, thanks to the critical role nickel plays in a variety of technologies [47]. Each innovation in casting technology has led to elevated usage temperatures. Columnar grains are generated analogous to the growth axis in DS treating. The usual development direction of nickel-based alloys is along the 100 > crystallographic direction. The Liquid metal is poured into a mold with a bottom plate which is water cooled to achieve this shape. The bottom plate solidifies first, then the mold is gently removed from the oven, permitting the metal inwards to solidify in a directed fashion from end to uppermost point. The outstanding qualities of DS and SC alloys are attributed to a combination of factors.

- Every fragile grain border placed crosswise to the ultimate filling direction must be aligned or eliminated.
- Inside the zones of confined thermal growth, such as turbine vanes, the small modulus related with the 100 > orientations improve thermal mechanical fatigue resistance. In general, the lack of transverse grain boundaries combined with a lower modulus can extend rupture life by 3-5 times.

SC casting was created in the 1970s because of technological advancements in the DS molding methods. SC moldings are made in the same way as DS castings, using a grain selector to pick a single grain. That sole grain expands to engulf the whole fragment after solidification. The removal of grain boundaries gives single crystals their exceptional strength. Furthermore, removing grain borderline strengtheners like C, B, Si, and Zr elevates the melting point of a single crystal. The homogenization heat treatment temperature can be raised without danger of initial melting by elevating the melting point of alloy, letting extra comprehensive solutioning of the Gamma' raising alloy capability and maximum usage temperature.

3.1.2. Chemical Composition of Nickel alloys

Most of the nickel-based alloys comprise of 10 to 20% Cr, approximately 8% Al and Ti, 5 to 10% Co, and a little bit quantity of B, Zr, and C. however, Mo, W, Ta, Hf, and Nb are also typical add-ons. The additional elements in Nickel base super alloys can be divided into categories: a) Gamma formers (elements that incline to divide to the Gamma matrix), b) Gamma' formers (elements that divide to the Gamma' precipitate), c) carbide formers, and d) grain boundary elements Group 5, 6, and 7 elements such as Co, Cr, Mo, W, and Fe are termed Gamma formers. These alloys have atomic diameters that are only 3% to 13% unlike Nickel (which is the primary matrix element). Al, Ti, Nb, Ta, and Hf are gamma' formers that come from group 3, 4, and 5 elements. These elements have atomic widths that are 6-18% smaller than Ni. Cr, W, Nb, Mo, Ta, and Ti are the most common carbide producers. B, C, and Zr are the principal grain boundary constituents. Their atomic breadths varied by iron to 21 to 27% [48,49].

The following are the primary phases found in most nickel super alloys:

Gamma: The gamma (continuous matrix) is a face centered cubic nickel based austenitic phase with a high fraction of solid solution elements including Cr, Co, W, and Mo.

Gamma Prime (Gamma') is a type of gamma ray. Ni3 (Al, Ti), also recognized as gamma prime (Gamma'), is the principal strengthening part of nickel-based super alloys. It possesses a systematic L12 crystal arrangement and is a rationally precipitating stage. The Gamma' may precipitate consistently all over the matrix and has long-term solidity because of the near counterpart in matrix or precipitate lattice parameter (0 to 1 percent) along with chemical compatibility. Surprisingly, Gamma' flow stress rises with growing temperature up to roughly 650C. (approx. 1200-degree F). Gamma' is also relatively ductile, therefore it adds power to the matrix devoid of compromising the alloy's fracture durability. The volume segment of Gamma' precipitate in some contemporary alloys is around 70%. Gamma' fault energy, Gamma' strength, coherency strains, Gamma' volume percentage, and Gamma' unit size are all parameters that contribute to the hardness imparted by the Gamma'.

Gamma' precipitates that are extremely tiny invariably appear as spheres. A spherical contains 1.24 surface area less than a cube for a given volume of precipitate, making it the best shape for minimizing surface energy. The interfacial energy of a coherent element, on the other hand, can be reduced by creating cubes and keeping the crystallographic surfaces of the cubic matrix and then precipitate endlessly. Depending on the magnitude of the matrix/precipitate lattice mismatch, the morphology of the Gamma' can modify from spheres to cubes or flat plates as it expands. The crucial unit size of the transition from spheres to cubes happening is minimized as the mismatch value increases. Over time, coherency can be lost.

Carbides are usually generated when carbon is injected at a concentration of 0.05 to 0.2% and reacts with refractory and reactive elements like Titanium, hafnium, and tantalum to generate carbides (such as TiC, HfC, or TaC). The crystal structure of all these common carbides is fcc. The results differ on whether carbides are harmful or

beneficial to superalloy characteristics. Carbides are thought to be useful in superalloys with grain boundaries because they increase rupture power on high temperatures.
Topologically close-packed phases:

While heat operations, these fragile stages can occur and are generally undesired. Closely filled atoms in form of layers which are detached by relatively short spaces characterize the cell structure of these phases due to large inter atomic spaces. Sheets of densely crowded atoms are evacuated from one another by bigger atoms sandwiched between them, causing a discrete "topology." The topologically close-packed (TCP) structure of these compounds has been identified.

TCPs (Sigma, Laves, and others) typically develop as plates. Mechanical qualities are harmed by the plate-like form (creep-rupture and ductility) [50]. Sigma appears to be the most harmful, although other alloys including mu and laves have shown strength retention. These phases can be injurious for two reasons: they fix Gamma and Gamma' reinforcing elements in an inactive state, lowering creep ability, and they can act as crack originators because of their delicate nature.

Table 3.1 Different grades of Nickel Alloys and their properties.

Different grades of nickel-based superalloys	**Chemical properties and characteristics**
Inconel 718	Precipitation hardens able, with high creep break strength and exceptional strength at high temperatures up to 700°C. Primary Niobium Carbide (NbC) precipitates, Titanium Carbide (TiC) disk-shaped gamma precipitates (Ni3Nb), and needle like niobium carbide (NbC) precipitates
Inconel 100	At 870°C, High rupture strength, precipitation harden able. The high proportions of Titanium, Aluminum, and a low-refractory metal boost the strength-to-density ratio.

Inconel 825	In an extensive variation of oxidizing and reducing circumstances, it has good resistance to pitting; inter granular, Chloride-ion stress corrosion cracking, and common corrosion.
IN-713LC	Due to gamma prime reinforcement increased by solid solution and grain boundary reinforcement, the material has an excellent mix of tensile and creep-rupture capabilities, as well as good castability.
Udimet 720LI	Tungsten and molybdenum are used to strengthen the solid solution, which is subsequently precipitation hardened with Titanium and Aluminum. High power, great impression strength maintenance at high temperatures, outstanding oxidation and corrosion resistance, and a high work hardening grade.
FGH95	At 650°C, precipitation hardened steel had better tensile and yield strength. In the grain, a compact structure containing grainy gamma prime phase precipitated beside prior particle boundaries appears after hot isostatic pressing (HIP).
ME-16	At high temperatures (600–800°C), it has excellent power and creep resistance. Also, at lower temperatures (300–600°C), there is extraordinary resistance to fatigue crack development. At high temperatures, it can keep its strength and lesser density.
RR1000	Chromium, molybdenum, and cobalt are used to fortify the solid solution. At high temperatures, it has good strength, toughness, creep resistance, oxidation, and corrosion resistance.

3.1.3 Markets and Applications of Nickel alloys

Nickel based alloys are commonly used in the aerospace, nuclear, marine, and petrochemical manufacturing plants to make critical components and structures. These alloys have become particularly important in hot areas of aero engines, such as compressor discs and gas turbine combustion chambers [51]. Inconel, Nimonic, Udimet, and Rene are nickel-based alloys that can be wrought, cast, or sintered to give outstanding high-temperature capability along with resistance against corrosion and oxidation. The most difficult-to-cut alloys are always referred to as such. Nickel-based superalloys have the greatest homologous temperature of any conventional alloy structure (Tm = 0.9/90% of its melting point) and are employed in load-bearing constructions to that temperature. The hot areas of turbine engines are among the most challenging applications for a structural design purpose.

Superalloys' dominance is evident in the fact that they now account for more than half of the mass of sophisticated aviation engines. The extensive usage of super alloys in turbine machines, along with the point that the thermodynamic effectiveness of turbine engines improves as turbine inlet temperatures rise, has fueled efforts to raise superalloys' maximum usage temperature. Actually, the temperature capability of turbine airfoils has increased by around 4°F every year on average during the last 30 years.

- Techniques which are more advanced leads to enhancing alloy cleanliness (thus boosting dependability) and/or create opportunity for the development of customized microstructures like directionally hardened or single crystal solid, are two significant causes that have enabled this improvement.
- Alloy development, especially through the addition of refractory elements for instance Re, W, Ta, and Mo, has given rise to in higher-use-temperature resources.

Advanced cooling concepts accounted for about 60% of the rise in use temperature, while material advances accounted for 40%. Surface temperatures of modern turbine blades reach approximately 2,100°F or 1,150°C, the maximum tough stress and temperature combinations correlate to an ordinary mass metal temperature of around 1,830°F or 1,000°C.

As the super alloys maintain their substantial capability applied temperatures approximate 1800°F, the presence of reactive alloying components makes them vulnerable to environmental attack (that is responsible for their high temperature durability). Hot corrosion, oxidation, and thermal fatigue are all examples of surface attack. In most of the challenging applications such as turbine blades and vanes, super alloys are frequently coated in order to increase resistance from environmental impacts.

Table 3.2 Applications of different Nickel alloys.

Different grades of nickel-based alloys	Markets	Uses/ Applications
Inconel 718	Aerospace Power generation	Aviation and aerospace industry In Liquid fueled rockets, rings, and casings Turbine engines sheets Cryogenic tankage High-speed airframe parts as wheels, fasteners, bolts, spacers etc.
Inconel 625	Marine systems Power generation Manufacturing pipelines	Steam liner bellows Undersea communication cables sheathing Auxiliary propulsion motors Submarines Ducting and exhaust systems Turbine shroud rings and seals

Inconel 825	Pipe industry Chemical industry Oil and gas industry	Heat exchangers for chemical processing Pollution control equipment Fuel element dissolvers Gas gathering pipes Scrubbers and dip pipes
IN-713-LC	Aerospace Power generation	Jet engines Gas turbines Blades Turbo blowers
Inconel 690	Nuclear industry Pipe industry Oil and gas industry	Petrochemical engineering Nuclear power Defense industries Transmission pipelines
FGH 95	Power generation	High pressure turbine blade retainers Power plants
RR1000	Aerospace Power generation	Disc in gas turbine engines aero -engine components As a turbine rotor

3.1.4 Advantages of Nickel Based Alloys

- a less rate of thermal expansion.
- have a good shape memory, the ability of a material to go back to its original shape after heating up
- exhibit magnetic permeability
- able to withstand extreme thermal conditions, without warping, corroding, or losing strength
- incredibly resistant to several different types of corrosion.
- Nickel is slow to oxidize at room temperature, so corrosion resistant

- resistant to reducing media, such as aggressive chemicals and seawater
- They are highly durable
- From welding point of view, Nickel alloys are relatively easy
- have an extensive variety of elements and hence offer a varied collection of mechanical characteristics
- They possess corrosion resistance which is generally good in both aerobic and anaerobic environments
- They are much more resistant to carburization
- Nickel-based materials fully support eco-efficiency at room temperature,
- Nickel is magnetic and has a high melting point.
- They are recyclable, can be converted into different yet valuable form
- Have high degree of toughness
- Can be turned or milled at high speed due to toughness
- Exhibit high specific strength
- Useful for metal investment casting

3.2. INCONEL-601

3.2.1 Characteristics of INCONEL-601

- At 2200° F possesses exceptional oxidation resistance
- When extreme thermal conditions in cycling are applied it resists spalling
- Carburization can't affect it
- creep rupture strength is good
- has metallurgical stability

3.2.2 Chemical composition of Inconel-601

Table 3.3 Chemical composition of Inconel 601.

Elements (%)	Ni~61.5	C~0. 05	Al~1. 4
Cr~22.5	Si~0.2	Mn~0. 3	Fe~14

3.2.3 Applications of Inconel-601

- Chemical Processing- insulating cans in ammonia reformers and equipment for nitric acid production, catalyst support grids
- Aerospace- turbocharger seals and rotors, rotary engines, exhaust systems of Formula 1 and NASCAR, gas containment rings and turbine blades, combustors and seals, igniters of jet engines, liners of combustion cans, and diffuser accumulates
- Power generation- super heater tube supports, ash handling and grid barriers
- Steam super heater tube supports
- Fixtures, trays, and baskets which are used in various heat handlings such as carbo-nitriding and carburizing, heat treating industry, muffles, and retort
- Thermal processing- strand annealing, refractory anchors, and radiant tubes, wire mesh belts, high velocity gas burners, etc.
- Petrochemical processing- thermal reactors in the petrol engine’s exhaust system, catalyst generators and air preheaters
- Pollution control equipment- fabricated combustion chambers, incinerators

Figure 3.1 Mazda RX7 turbocharger rotor.

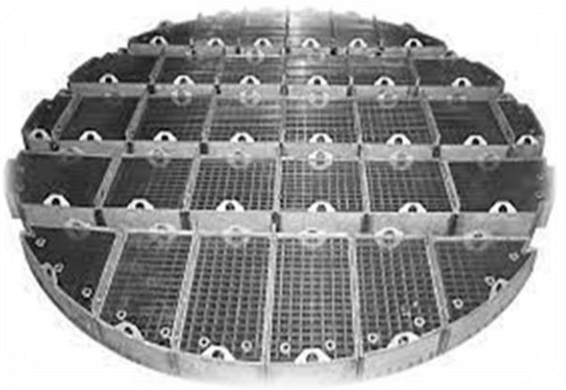


Figure 3.2 Catalyst support grid.

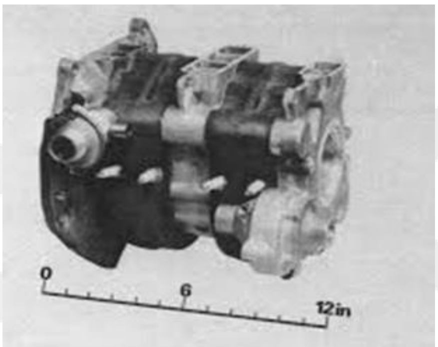


Figure 3.3 Norton engine Rotary.

Figure 3.4 Fixture used in Carburizing.

Figure 3.5 Jet engine igniter.

3.2.4 Mechanical properties of Inconel-601

Table 3.4 Properties of Inconel 601.

Ultimate tensile	80 ksi-550 MPa
Yield strength	30 ksi-205 MPa
Electrical Resistivity	119 m ohm cm
Specific Heat	461 Joule per Kilogram Kelvin
Density	8.1 gram per centimeter cube
Curie Temperature	-190 degree Celsius
Melting Range	1320 to 1370 Celsius
Thermal Expansion	14.9 (20-300 C)

3.3. CUTTING CONDITIONS IN TURNING

Machining is the practice of removing material from a workpiece using power consuming machining tools to mold it in a desired shape. Milling, drilling, turning, and other processes are included in this category [52,53]. The process of spinning a work piece on a machine while keeping a one-edged cutting tool immobile is known as lathing. The cutting tool is gently pushed analogous to the work piece's rotational axis, eliminating material when it goes.

One of the most significant machining processes is turning. It is carried out using a variety of machine tools, with varying machining parameters and cutting tools and fixtures. It is most commonly used for cutting cylindrical pieces, but it can also be used on prism and complicated work piece geometries. Workpiece materials can be brittle/tough, soft, or hard, difficult or easy to machine, and so on. Rough or finishing regimens can be used to manufacture workpieces. Furthermore, a huge number of work pieces can be turned to their final measurements without the need for further finishing procedures such as grinding, honing, and so on, resulting in considerable time and cost savings [1].

Selecting the right cutting conditions for a specific action is one of the practical difficulties in machining [54]. The selection of these conditions, given the work material and tooling, has a noteworthy influence on the success of a machining procedure. A machining operation's cutting conditions include speed, feed, cut depth, and cutting fluid.

Short cutting times, great cutting precision, long tool life are perfect cutting conditions. Selecting desirable cutting tools and conditions, founded on work material, form, hardness, and machinability, is required to attain these environments. For lubrication and cooling of the cutting tool, a cutting fluid is frequently used throughout the machining process [55]. Cutting conditions normally comprise determining if a cutting fluid ought to be used and selecting the appropriate cutting fluid. When it comes to cutting fluids, tooling is frequently the most important factor. Following are the cutting conditions for turning:

Cutting speed:

The tool's speed of cutting (written as v) is the rate at which the metal is detached from the tool. Cutting speed has a substantial influence on tool life. Cutting temperature can be raised at a faster speed, which lessens tool life. The cutting speed differs founded on the nature and rigidity of work material. It is important to select a tool ranking that is suitable for the cutting speed. The cutting speed is determined by creating the greatest usage of the cutting tool, which usually entails selecting a speed that delivers a high rate of metal removal while maintaining a suitable tool life. Assumed that the several cost and time factors of the process are well-known, mathematical methods have been developed to estimate the ideal cutting speed for a machining operation. The best cutting speed can be computed using W. Gilbert's methods for one of two goals: maximum output rate or minimal unit cost. Both goals aim to strike a compromise between tool life and material removal rate.

Cutting Speed's Effects:

- The tool life reduces to 50% by increasing the cutting speed by 20 %. The Tool life is reduced by 80% when we increase the speed of cutting by 50 %.
- Chattering can be produced by cutting at a very low speed (20 to 40 m/min). Consequently, tool life is reduced.

Feed rate:

Feed rate is defined as the distance at which a holder changes every work piece revolution while cutting with a common type of holder. The area a machine table travels each cutter revolution divided by the number of insertions is the feed in milling. Accordingly, it's transcribed as feed per tooth. Finished surface roughness is related to feed rate. In a lathe job, the feed of a cutting tool refers to how far the tool spreads with each revolution of the work. The feed rate is measured in mm per revolution. Cutting time is reduced when the feed rate is increased.

The following considerations have a role in defining the optimal feed rate intended for a specific machining process:

- Tooling is important; harder tool materials (for instance cemented carbides, ceramics, and so on) are more prone to fracture than high speed steel. Normally, these apparatuses are utilized at a bit low feed rate. Because of its superior durability, HSS can endure higher temperatures.
- Roughing it out or putting the finishing touches on it. Roughing activities require high speeds, such as 0.5-1.25 mm per rev for turning, whereas surface operations require lower feed rates, such as 0.125-0.4 mm per rev for the turning.
- Feed limitations in roughing and feed should be set as high as possible to enhance metal removal rate. Cutting forces, setup rigidity, and sometimes horsepower imposes upper feed restrictions.
- Finishing criteria for the surface texture; Surface finish is affected by feed, and simulations can be used to assess the feed required to achieve an anticipated surface roughness.

Feed Rate Effects:

- Lowering the feed rate causes tool wear and reduces the tool's life.
- Increase in the feed rate raises the temperature of cutting and flanks wear. Yet, when compared to cutting speed, the effects on tool life are minor. Increase in the feed rate develops the effectiveness of the machining process.

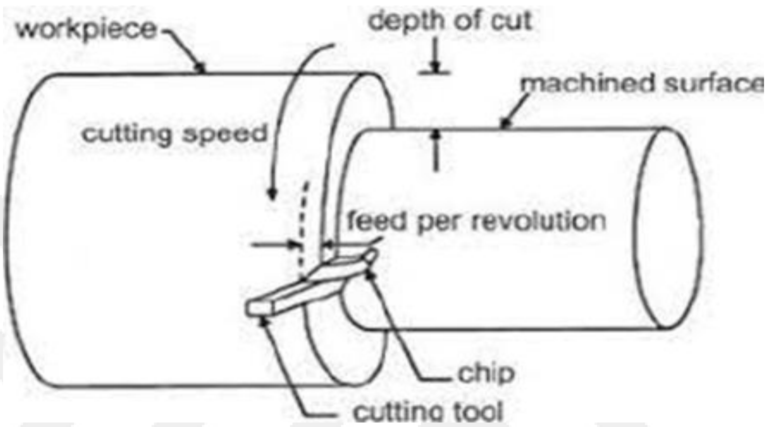


Figure 3.6 Feed, cutting speed and cut depth for a turning process [7].

Depth of Cut:

The cut depth is evaluated by the quantity of material, which is to be removed, form of the work piece, tool's rigidity and the machine's power and stiffness. The distance that is perpendicular area as measured from the machining surface to the uncut surface of the work piece is called the cut depth. The depth of cut is frequently determined by the geometry of the work piece and the order in which operations are performed. Many jobs necessitate a series of roughing processes before completion operation. Following roughing actions, a final finishing process is performed. During the roughing operations, the depth is increased as much as feasible contained by the constraints of the project; Machine tool and structure stiffness, cutting tool power, and available horsepower and so on. The depth of the finishing cut is selected to obtain the part's final dimensions. The challenge is therefore reduced to feed and speed selection. The following parameters ought to be chosen in the following sequence: feed at first, second speed.

Effects of Cut Depth:

- Changing the cut depth has slight impact on tool life.
- The cutting of the tough layer of a work piece with small depths of cut causes friction. As a result, the tool's lifespan is reduced.
- As soon as cutting uncut areas or cast-iron planes, increase the cut depth as far as the appliance power permits to elude cutting of impure hard areas with cutting edge's tip, which can cause chipping and abnormal wear [56].

Turning operation:

Rotational speed of the turning operation is measured by the following equation:

$$fr = N * f \tag{3.1}$$

Where fr is feed rate, N is rotating speed in RPMs and f is feed.

Machining time of the turning operation can be measured by the equation given below: Where ™ is time of machining, L is cut length and fr is the feed rate. Now, rate of material removal can also be found by using the given formula:

$$MRR = v * f * d \tag{3.2}$$

Where M.R.R is material removal rate, [v] is cutting speed, [f] is feed and [d] is depth of cut [57].

3.4. COOLING CONDITIONS

Numerous studies have concurred that minimal quantity lubrication (MQL) can be used in place of typical flood coolants in machining operations. Regarding sustainable production, MQL is viewed as a useful tool for developing cleaner manufacturing processes. Additionally, this technology combines cooling agent effectiveness with extremely negligible levels of consumption, making it easy for production in an inexpensive and environmentally friendly manner [58,59]. Due to the demands for sustainability and minimal oil usage, it is crucial that MQL fluid has the characteristics of high stability, high lubrication, and biodegradability.

According to whether fluid is provided internally or externally, MQL is divided into several categories, as shown in the following figure. In order to ensure continuous spraying of CFs into the cutting zone, the first type is more frequently utilized for machining operations like turning and milling when the l/d ratio (l = depth of the hole, d = diameter of a hole) is below three. For drilling, reaming, and tapping milling, on the other hand, internal supply systems work best when the l/d ratio is more than three [60]. However, in the case of deep hole drilling, when specific issues arise during machining processes [61] that call for a range of tools with various sizes, cutting fluids is continuously used in internal supply ways to enable the drilling of extremely deep holes at fast cutting speeds.

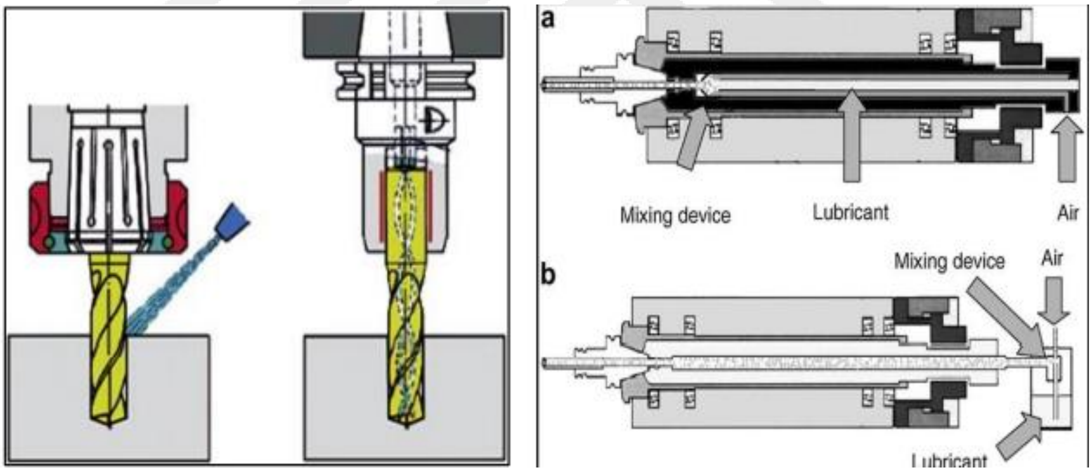


Figure 3.7 MQL and cooling conditions [40].

The MQL method is a synthesis of several cutting fluids used as a buffer in compressed form [62]. To cool and lubricate the contact, plain oil or oil emulsions are often added in water at different concentrations. MQL is a widely utilized technique for every machining operation since cutting fluid are directly sprinkled into the cutting area in this manner [23].

3.5. TRIBOLOGICAL CHARACTERISTICS

3.5.1. Tool Wear

Tool wear can be described as "the gradual loss of tool material during cutting, resulting in a change in shape of the cutting part of a tool from its original shape". Tool wear is among the most significant and a complicated component of every machining procedure and it is affected by a range of aspects. The tool and workpiece's physical, chemical, and mechanical qualities, as well as cutting fluid characteristics, tool geometry, and several other operational factors with the type of machine based on the proportional importance of these variables. There is a significant amount of difficulty, as a result of analytically investigating tool wear, knowledge of tool wear is mostly based on test results. The following are some of the most common tool wear mechanisms [63]:

3.5.1.1. Abrasive wear

In abrasive machining, abrasive wear refers to the loss of material due to the creation of chips, which is primarily generated by gliding rigid units against the cutting tool. The rigid particles can originate from the work piece material or from broken-off pieces of the cutting edge [64].

3.5.1.2. Adhesive wear

If the connections created between the planes are durable than the material's local power, a particle may pass from one surface to the other when a mating pair of surfaces gets near together. This kind of wear is known as adhesive or attritious wear [65].

3.5.1.3. Diffusive Wear

Diffusive wear happens when particles from the material of cutting tool seep into the chip's bottom, or atoms from the work piece material diffuse into and rejoin with the tool's surface strata, causing the tool's microstructure and hence strength to be altered.

The rate of diffusive wear is determined by the material combination of the tool and the work piece, as well as their solubility, temperature, pressure, and time. Diffusion is also temperature-dependent, occurring more quickly at higher temperatures generated by faster cutting speeds, which are frequently obscured by plastic deformation.

3.5.1.4. Fatigue Wear

Fatigue Wear is induced by recurring thermal or mechanical masses on the tool, and it is particularly critical in interjected cutting activities like milling, where the force and temperature generating on the cutting-edge change during the tool's revolution. When multiple small fissures in succession at right angles to the cutting edge are seen, thermal fatigue is generally suspected.

3.5.1.5. Plastic Deformation

High temperatures and strains on the cutting-edge cause plastic deformation, that is not exactly a wear procedure because nothing is lost from the tool. Deformation normally begins at the tool’s nose and progresses to the cutting edge, resulting in increased temperatures and pressures. When cutting at high speeds and feed rates, resulting in high generated cutting temperatures, or when machining hard materials, plastic deformation is a frequent wear mechanism. So, a cutting tool with a high warm rigidity has to bear plastic deformation.

In addition to its alloys, titanium might benefit from a variety of surface treatments. Here are a handful of the most popular coatings: plating, chemical conversion coatings, sprayed coatings, and physical vapor deposition (PVD) [66]. Utilizing surface coatings permits enhancements in corrosion resistance, lubricity, titanium wear properties, and heat resistance. Surface coating methods need decent adhesion and any advantage obtained from coatings would only persist if the coating remained intact.

3.5.2. Surface Roughness

The Surface roughness of the tool is a distinctive feature of surface texture which is measured by the deviances in the direction of a real surface's normal vector from its ideal system. The exterior is rough if these alterations are considerable; the surface is even if they are negligible. Surface roughness is frequently assumed as the high-frequency and a short-wavelength factor of a measured surface in the surface metrology [67].

Because abnormalities on the surface can perform as nucleation spots for cracks or the corrosion, and roughness is often a strong interpreter of a mechanical factor's performance [68]. Roughness, on the other hand, may encourage adherence. In general, cross-scale descriptors such as surface roughness, rather than scale-specific descriptors, deliver more relevant estimates of mechanical contacts at the surfaces [69], such as contact toughness, rigidity and static friction. Although a high roughness value is frequently desired, it is problematic to control and costly. After a decrease in surface's roughness, the charge of making it rises. This frequently indicates a tradeoff between a constituent's manufacturing cost and its performance in usage [70].

The goal of machining is to produce a part with the appropriate geometry, dimensions, and dimensional tolerances [71]. Surface polish is also required for proper part operation. Additionally, the surface must be free of fissures, residual tensions, and unwanted metallurgical changes. The mean of vertical deviations from the normal surface over an exact surface length is known as surface roughness. Centered on the complete values of the deviations, an arithmetic average (AA) is commonly utilized, and the roughness value is denoted as average roughness. In the form of an equation,

$$R_a = \int_0^{Lm} \frac{|y|}{Lm} dx \tag{3.3}$$

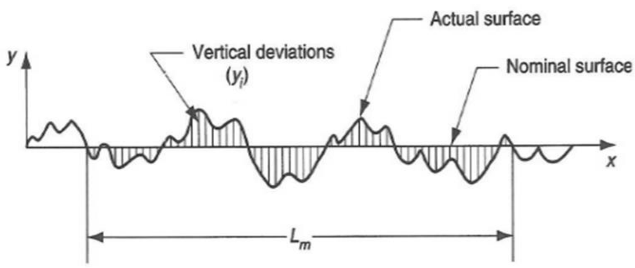


Figure 3.8 Surface roughness [9].

While Ra is the Arithmetic Mean roughness value, m, y is the Vertical Deviation from the nominal surface (transformed to absolute value), m, and Lm is the Specified Distance above which the surface deviations are measured.

$$R_a = \sum_{i=1}^{n} \frac{|yi|}{n} \tag{3.4}$$

where Ra is the same as above; yi is the number of deviations included in Lm; and n is the number of deviations changed to absolute value and indicated by the subscript I m. These equations use meters and inches as units. Because the scale of the deviations is so small, m (m= m x 10 -6 = mm x 10 -3) is a more appropriate unit. This is the standard unit for expressing surface roughness.

Ideal roughness is 0 in the longitudinal direction. Other roughness-inducing elements are introduced into the workpiece during real cutting.

- When cutting with discontinuous chips at moderate speeds, cracks form perpendicular to the cutting direction.
- When using the Built-up Edge BUE to cut the workpiece, certain particles are fused to the surface. Ceramic and diamond tools produce a better surface polish than other tools, owing to their lesser proclivity for forming a BUE.
- Cutting with no BUE and a continuous chip gets close to being ideal, but roughness is caused by localized tool edge wear or chipping.
- Chatter introduces surface geometry changes.
- Tool wear affects the surface finish.

Depended on the deviations of roughness outlined above, the surface roughness is a measurable feature. Surface roughness is an important quality parameter in machining processes and is a technical requirement for many goods [72]. Surface roughness formation is a complicated process that is influenced by a variety of circumstances [73]. Surface roughness is defined as a variation from the nominal surface in the 3rd to 6th order. International standards establish the order of deviation. 1st and 2nd order deviations denote form, waviness, flatness, obliqueness and are caused by machine tool mistakes, workpiece deformation, incorrect setups and clamps, vibration, and workpiece material in homogeneities, respectively. Episodic grooves, cracks, and derelictions are examples of third and fourth-order aberrations, and condition of the cutting edges and shape are linked to chip production, and process kinematics. Work piece material organization is linked to physical chemical phenomena acting on a grain and lattice scale in fifth- and sixth-order aberrations. The surface roughness profile is formed by superimposing different order deviations.

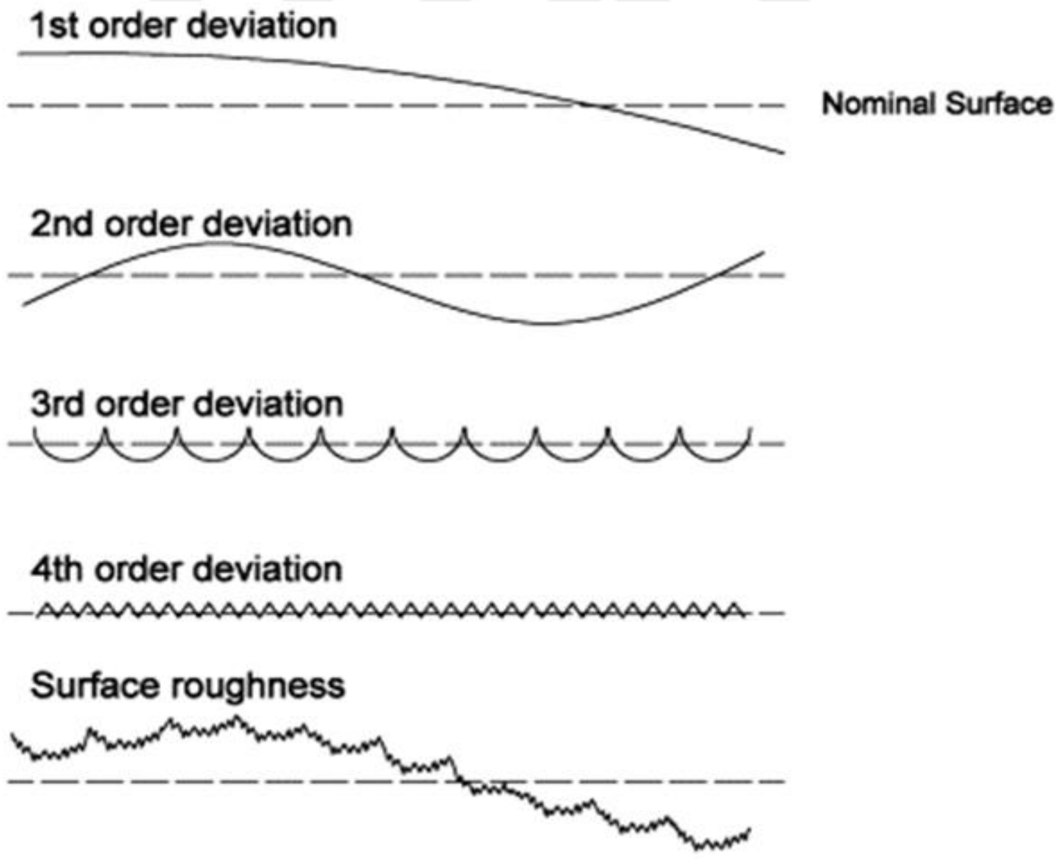


Figure 3.9 Different orders of deviations in surface roughness [74].

Surface roughness has the same flaws as any other single metric used to evaluate a complicated physical feature [53]. Waviness can be involved in the Ra calculation, which is another flaw. To solve this problem, a filter called the cutoff length is utilized to detach the waviness of a measured surface from the roughness variations. Vertical deviations connected with waviness will be eliminated if the sampling distance is less than the waviness width, leaving only those associated with roughness. The optimal transverse roughness of a tool with a corner radius R moving over a surface with feed f can be calculated as follows:

$$R_{max} = \frac{f^2}{8R} \tag{3.5}$$

$$R_a = R_{\frac{max}{4}} = \frac{f^2}{32R} \tag{3.6}$$

3.5.3. Temperature

Almost all of the energy used for machining—about 98%—is transformed into heat. At the tool chip contact, temperatures as high as 600oC are not unusual due to this heat. The remaining energy (less than 2%) is stored in the semiconductor as elastic energy.

Because of the significant negative impacts, it can have during machining, including the following:

- Shorten tool life, the cutting tool's strength, hardness, stiffness, and resistance to wear decrease with increased temperature. Tools may also soften and experience plastic deformation, changing their shape.
- As heat builds up throughout the machining process, the part's dimensions fluctuate unevenly, making it challenging to maintain dimensional precision and tolerances.
- Thermal damage and metallurgical changes to the machined surface might result from an extreme temperature rise, which will negatively alter the surface's qualities.

- Generating high temperature chips that put the machine operator's health and safety in danger.

The main sources of heat in machining are: (a) the work done in shearing in the primary shear zone, (b) energy dissipated as friction at the tool-chip interface, and (c) heat generated as the tool rub against the machined surface, especially for dull or worn tools. Detailed calculations show that the maximum temperature is developed at the rake face some distance away from the tool nose but before the chip lifts away.

During the machining process, following are the critical sources where heat is being generated:

- Shearing work in the primary shear zone
- Energy loss could be elaborated as friction at the interface between the tool and the insert.
- The heat generated when the tool rubs the machined surface, especially for blunt or worn tools. Before the chip lifts up and little distant from tool nose, high temperature develops at rake face of the tool.

3.5.4. Power Consumption

Manufacturers, particularly machining centers, would protect money and turn out to be more environmentally friendly if they reduced power use. Machining operations should collect data on power consumption in order to achieve this goal. Power consumption during machining can be measured in a variety of methods [75]. It's worth noting that powering motors and driving cutting tools consumes two-thirds of the total electricity. After roughing, this power usage is high, but it drops dramatically while finishing. It means that the cutting factors you choose have a direct impact on how much power you use. Calculating the power intake of machining methods is difficult because it must consider all components of the process, including the work piece, the tool, and the machinist.

In a machining procedure, the energy is required to work machine tool constituents (such as the feed axis, spindle, and control unit) to perform a chain of processes (e.g., loading, cutting, set up, automatic tool change). Previous research has shown that during machining processes, power usage is dynamic. The power consumption profile, on the other hand, may split into three sets: peak, constant, and variable power. Peak power is typically brief and accounts for a minor part of total energy consumption; hence, it can be neglected once estimating total energy consumption. The power requirement can be divided into two categories: variable and constant power.

The energy required for material removal techniques has been reported to be fairly low when compared to the total amount of energy required during the machining process. It has been also indicated that the energy mark of main material fabrication procedures is typically greater than that of secondary shaping processes[76]. Regardless of this issue, the raw material inputs for manufacturing organizations are generally set by way of the client, and energy calculations ought only to be concentrated on secondary production procedures, such as machining. Cutting force in turning process can be further resolved into its three components:

- Tangential component
- Radial component
- Axial component

The tangential component Ft is in the path of the cutting speed vector, the radial component is in the track of the job's radius as the name implies, and the third component is parallel to the job's axis, i.e., in the feed direction. The radial component of force does not work in turning since there is no radial movement of the tool. The other two components complete the task; however, the feed velocity is so low that the product of the feed force and feet velocity is insignificant when compared to the purposeful force and cutting velocity.

Power needed for turning = tangential force component X cutting velocity

$$P = \frac{F_t \times v}{60} \tag{3.7}$$

Where force is in Newton and Velocity is in m/min.

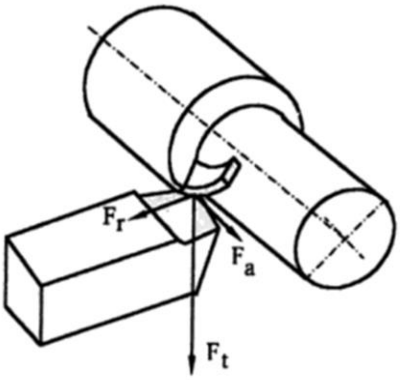


Figure 3.10 Vector representations of Forces in Turning operation [77].

The components of turning force can be expressed in exponential form which involve feed and depth of the cut[77]:

$$F_t = R_1 f^{x1} d^{y_1} \tag{3.8}$$

$$F_a = R_2 f^{x2} d^{y_2} \tag{3.9}$$

$$F_r = R_3 f^{x_3} d^{y_3} \tag{3.10}$$

PART 4

MATERIALS AND METHODS

4.1. MACHINING PROCESS VARIABLES

4.1.1 Input Variables

Input variables of the machining process are the variables independent of the procedure. Numerous categories of input variables are

Table 4.1 Machining input variables.

Machining input variables	**Parameters**
Cutting Conditions	Feed Rate, Cutting Speed, Depth of Cut
Machine tool	Accuracy, capability, rigidity and so on
Cutting tool	Material, geometry, tool rigidity, coating, nature of handling with the work material etc.
Cutting fluid	Characteristics as well as properties
Workpiece material properties	Hardness, microstructure, chemical composition, tensile strength, thermal conductivity, way of manufacturing, ductility, shape, scopes of the work, workpiece material stiffness etc.

4.1.2 Output Variables

Output variables of the machining process are the variables dependent on procedure consisting of the succeeding:

- tool life, tool wear and its rate
- Temperature of cutting
- Chip Characteristics
- Vibration
- Noise
- Processed Surface Finish
- Cutting Forces/ Specific Cutting Forces
- Material Removal Rate (MRR)
- Processed Dimensional Accuracy
- Power Consumption/ Specific Power Consumption

Machining is an exceptional plastic deformation process in that it is solely guarded by the cutting tool and operates at extremely large stresses and rates. Because there are so many different input variables, there are practically an endless number of potential machining combinations, making the process of identifying the relationship between input variables and process behavior complicated. Experience, investigations, and theories aid a production engineer in comprehending these relationships.

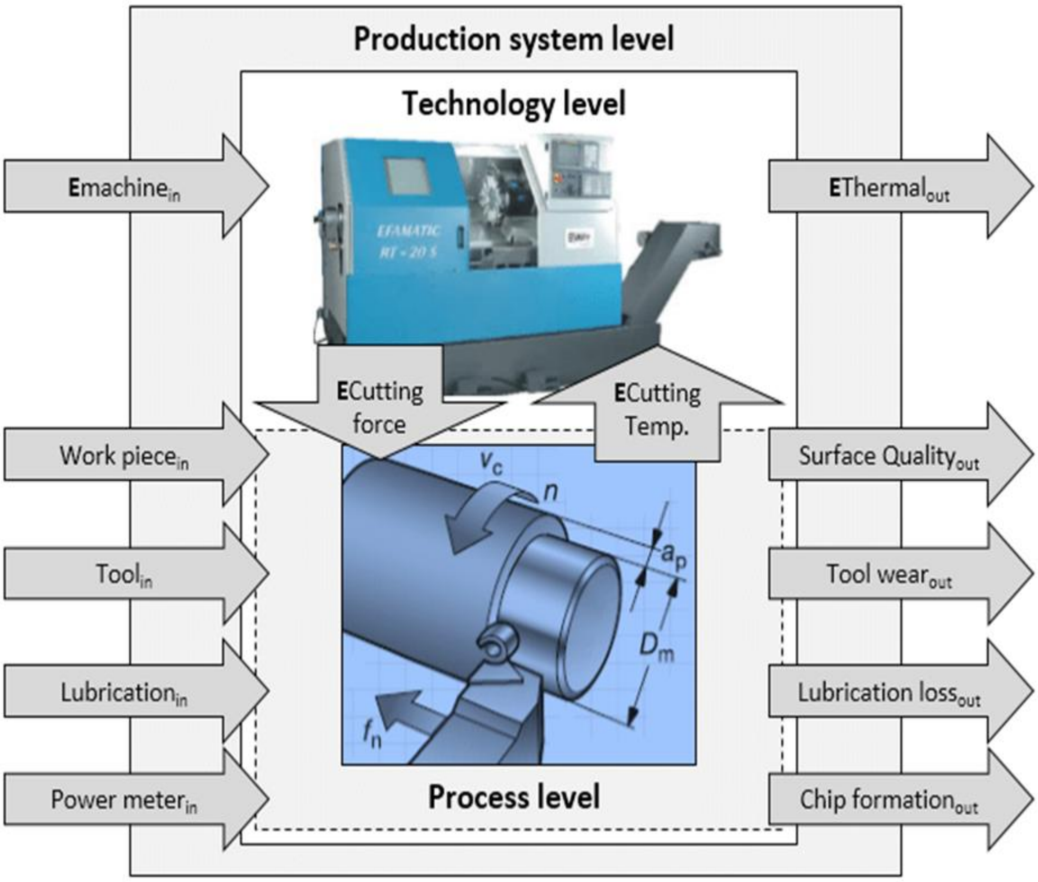


Figure 4.1 machining process parameters [78].

The majority of knowledge is obtained through trial and error, with successful combinations being applied to other similar situations. Experiments involving machining are typically costly, time-consuming, and complex to complete. Some tool life equations, on the other hand, have been empirically constructed by holding all input variables constant except speed.

It should be noted that input factors of the machining process may not accurately reflect machinability. The materials with the same configuration but a changed metallographic structure, for example, may have varied machinability properties. Furthermore, because output variables of machining method are results of input factors of machining procedure, the machining method output variables have been preferred by the majority of researchers for evaluating the machinability of work materials.

4.2. EXPERIMENTAL PARAMETERS

Table 4.2 Experimental conditions for the process.

Work specimen	INCONEL 601
Materials	Nickel (62.5%), Chromium (22.5%), Aluminum (1.5%), Carbon (0.10%), Manganese (1%), Sulphur (0.015%), Silicon (0.50%), Copper (1%), Iron (Remainder)
Size	Φ 60X250mm Cylindrical bars with a diameter of 60 mm and length of 250 mm
Cutting tool (insert)	CNMG 120404-PM 4225
Cutting speed	60, 80, 100
Feed rate	0.8, 0.12
Depth of cut	0.25
Environment	Dry, Mql, Nano-MQL mix, Cryogenic

4.3. OVERALL PROCEDURE

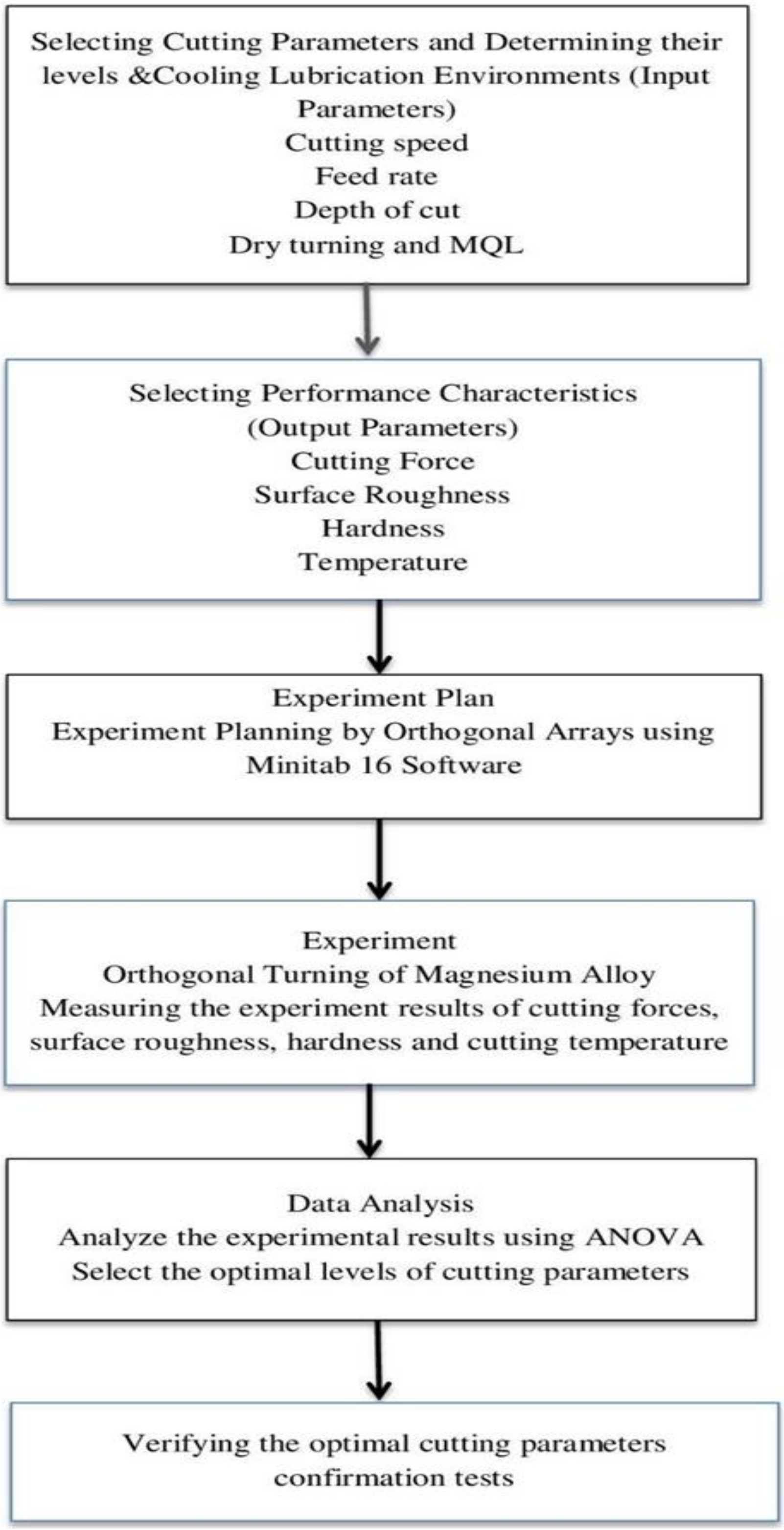


Figure 4.2 Overall experimental procedure.

4.4. WORKPIECE (INCONEL-601) MATERIAL DETAIL

Inconel601 is a Ni and Cr alloy that is utilized in fields that demand heat and corrosion resistance. The nickel alloy is notable for its resistance to oxidation at high temperatures, staying extremely resistant to oxidation up to 2200° F. Even under intense heat cycling, Alloy601 forms a strongly adhering oxide scale that repels spalling. Inconel 601 possesses good high-temperature strength and maintains its ductility. It has excellent corrosion resistance for aqueous solutions, elevated mechanical power, and capability, is easy to form, machine, and weld. The qualities of Inconel 601 make it a versatile material that may be utilized in a variety of markets including chemical treating, pollution controlling, thermal treating, power production and aerospace. However, alloy601 is not recommended for usage in Sulphur-bearing, severely reducing conditions.

INCONEL601 has a high degree of metallurgical stability and a face-centered cubic shape and is a solid-solution alloy with. Chromium carbides and titanium nitrides are common phases in the alloy's microstructure. A particle of titanium nitride can be seen in the photomicrograph as a big block-like structure. Chromium carbides are the little particles strewn about. The embrittling intermetallic phases such as sigma are absent, as been demonstrated in INCONEL alloy 601.

Carburization resistance is good in INCONEL alloy 601. The weight-gain data show how much carbon the specimens absorbed during the exposure periods. Carbo-nitriding conditions are also well-suited to Alloy 601. Sulfidation resistance of INCONEL alloy 601 at high temperature ranging (650-760°C) in an environment containing 1.5 percent hydrogen sulphide and 98.5 percent hydrogen. After 100 hours of exposure to the environment, the weight loss measurements are for totally descaled specimens.

In this study, the turning tests were performed on workpieces which were cylindrical bars of 60mm diameter and 250 mm length of Nickel based alloy, Inconel 601 as shown below:

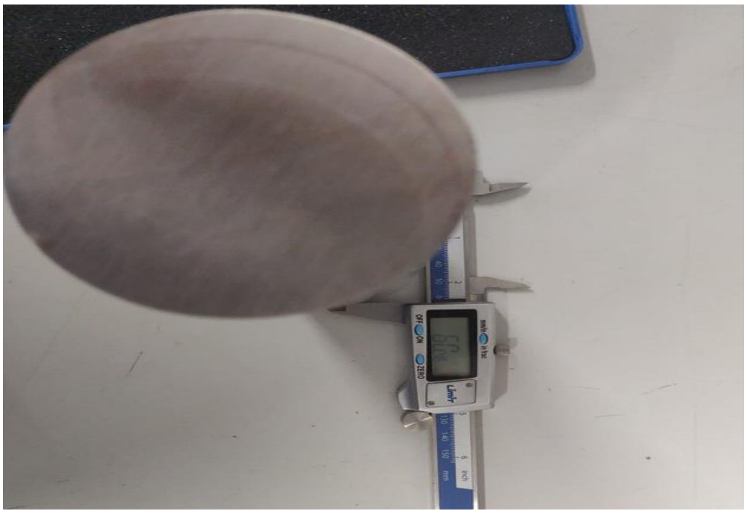


Figure 4.3 Diameter of Inconel 601 cylindirical bar.

Figure 4.4 Length of Inconel 601 bar.

4.5. INSERT TOOL MATERIAL DETAIL

Sandvik CNMG 120404-PM Carbide metal turning tool was used with high twisting resistance and resistance against wear, it is particularly used for extraordinary rigidity, high-speed cutting procedures. Below is the technical illustration of tool:

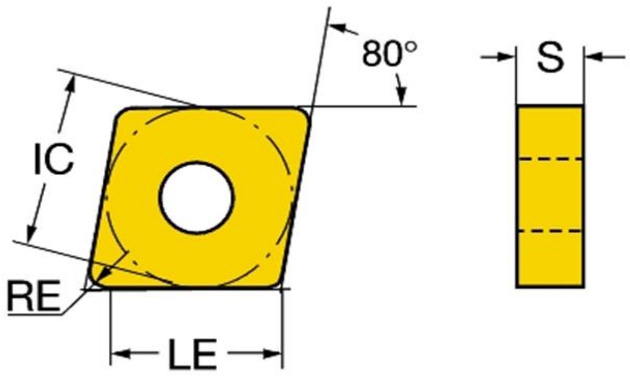


Figure 4.5 Generic representation of tool.

Table 4.3 Product data of Cutting Insert.

Material classification level 1(TMC1ISO)	PK
Operation type (CTPT)	Medium
Insert mounting style code (IFS)	2
Fixing hole diameter(D1)	5.156 mm
Insert size and shape (CUTINTSIZESHAPE)	CN1204
Cutting edge count (CEDC)	4
Inscribed circle diameter (IC)	12.7 mm
(ISC) Code of shape insert	C
Cutting edge effective length	12.496 mm
Corner radius	0.397 mm
Wiper edge property	False
Hand	N
Grade	4225
Substrate	HC
Coating	CVD TiCN+Al2O3+TiN
Insert thickness	4.762 mm
major Clearance angle	0 degree
Sensor embedded property (SEP)	0
Weight of item (WT)	0.009 kg
Release date (ValFrom20)	2005-10-10

4.6 EXPERIMENTAL SETUP

CNC turning was used to perform in our experiment. 8 minute machining time was taken for the experiment. This is due to the reason to check and analyze the tribological characteristics in the worst condition. Experimental setup is shown in the figure 4.6:

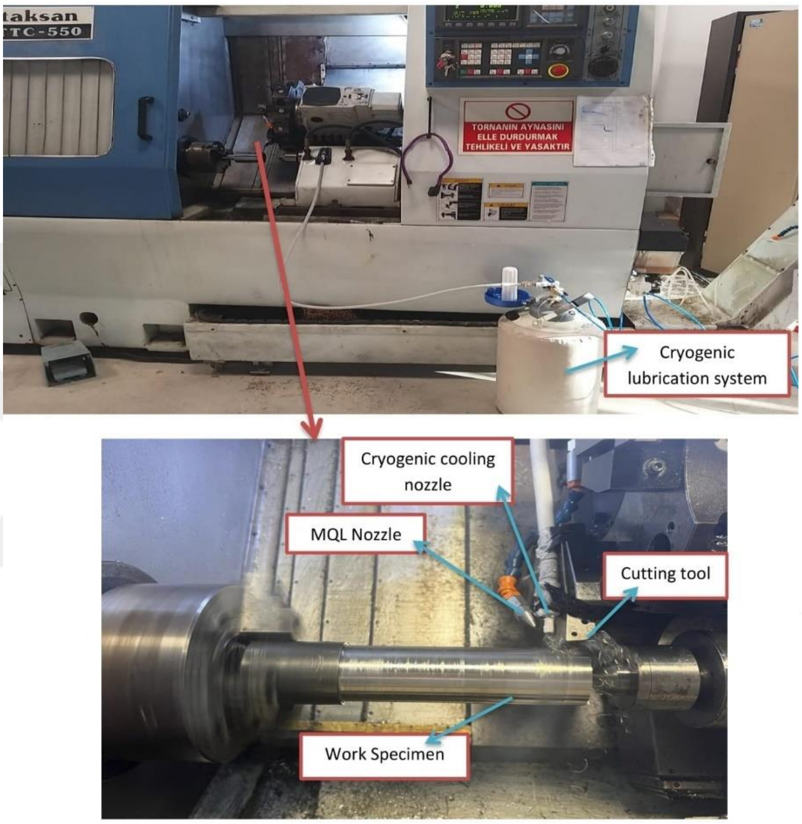


Figure 4.6 Experimental setup.

4.7 COOLING/LUBRICATION MECHANISM

4.7.1 MQL

MQL is a well-considered cooling technique that is also environmentally harmless[10]. Additionally, many investigations found that MQL cooling may provide machinability that is comparable to or even better than that of conventional wet or dry machining[51]. Studies on the application of the MQL method for cutting and machining various alloys, including titanium, have been done[79].

4.7.2 Nano-MQL

Nanoparticles have been used as lubrication additives to reduce wear and friction [3]. These additives have the potential to reduce wear and friction in aerospace, automotive, and other industrial applications [80]. Positive grades of friction adapting, and anti-wear effects have been established by nanoparticles of various materials and compositions[3]. Regarding an operational lubricant, a stable nanoparticle suspension is crucial[81].The addition of nanoparticles to lubricants greatly reduces the coefficient of friction and increases the capacity of load bearing for the friction components inside mechanical systems[82]. Such systems require lubricants that are extremely effective and ecologically friendly in order to maintain consistent operation and conserve energy. Due to their potential to lower emissions, nanoparticles started to demonstrate more significant roles as lubricating additives in recent years[83]. Due to its capacity to reduce both friction and wear of various materials, graphene and boron nitride nanoparticles have been used as lubricant additives by several studies[84].

4.7.3 Cryogenic

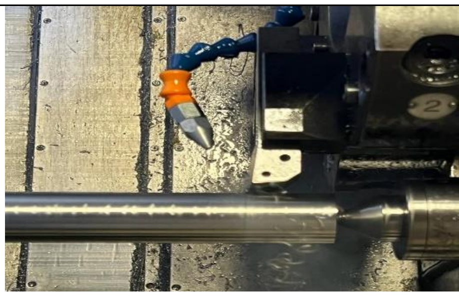
It is anticipated that gas-based metal cutting fluids will have less heat removal energy than minimum quantity lubrication (MQL) spray because they have a smaller specific heat capacity and average molecular density. It is anticipated that gas-based metal cutting fluids will have less heat removal energy than minimum quantity lubrication (MQL) spray because they have a smaller specific heat capacity and average molecular density. By designing a cryogenic cooli1324ng system for the cutting tool, Wang and Rajurkar (2000) improved tool life after demonstrating low tool life when turning Ti6Al4V and Inconel 718.

They argued that preserving the strength and hardness of the cutting tool material involved keeping tool temperatures at lower ranges[85]. The target site of cryogenic cooling plays a significant influence in reducing the temperature of the tool, according to Hong and Ding's (2001) investigation of various cryogenic cooling techniques[86]. When turning Ti6Al4V, Venugopal et al. (2007) demonstrated the development of various types of tool wear and short tool lives and looked at the efficacy of cryogenic turning[87].

4.7.4 Experimental Cooling Setup

In our experiment, several machining environments were studied. Dry, MQL, NANO-MQL and Cryogenic.

Table 4.4 Machining environment conditions.

Machining type	Setup
DRY	
MQL	
NANO MQL	
CRYOGENIC	

PART 5

RESULTS AND DISCUSSION

5.1. SURFACE ROUGHNESS

The smooth operation of components is significantly influenced by surface roughness. Variations in cutting parameters and cooling conditions have a significant impact on surface roughness values. Increased tool wear may cause Ra roughness levels to gradually increase, causing a less smooth surface. The graph 5.1 and 5.2 below shows the variation in Ra for Inconel 601 hard turning under varied cooling and lubricating conditions.

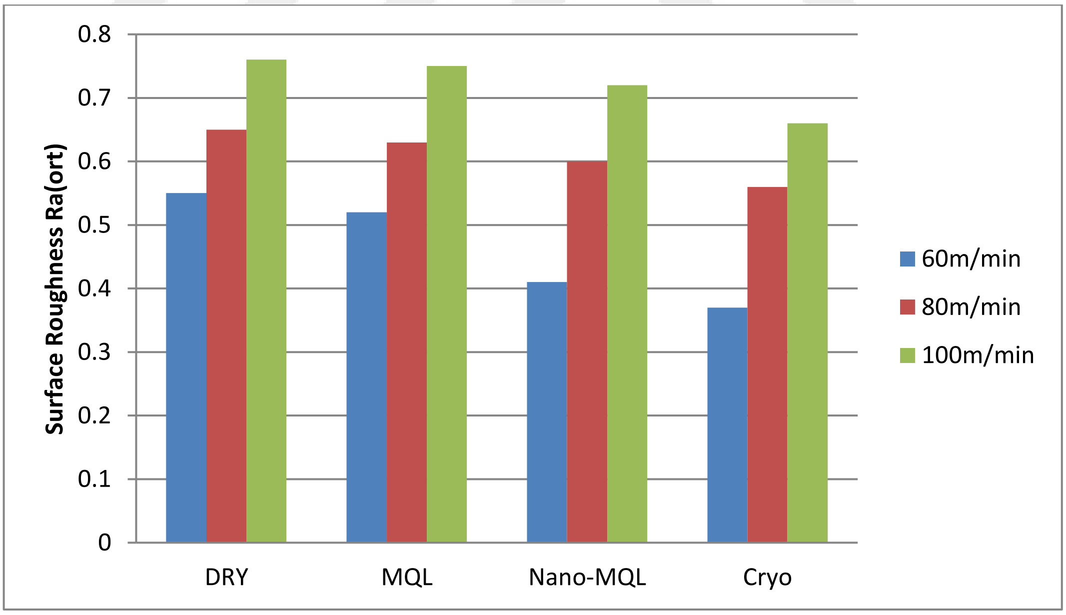


Figure 5.1 Ra at feed rate 0.08 mm/rev under various conditions.

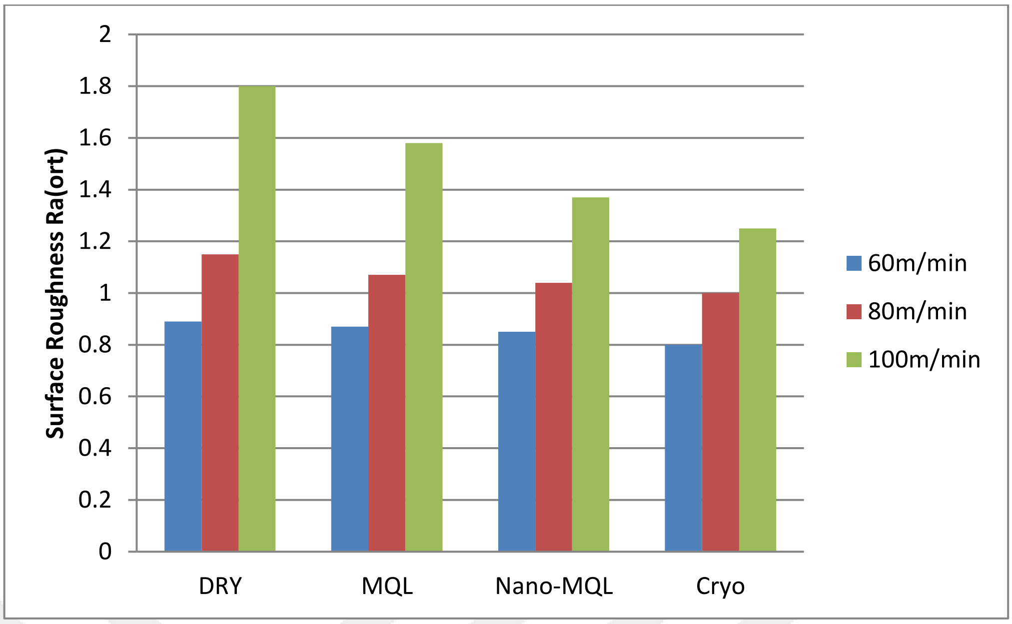


Figure 5.2 Ra at feed rate 0.12 mm/rev under various conditions.

According to the Figure 5.1 and 5.2, the best surface roughness value (0.37 µm) is obtained at 60 m/min with Cryo cooling conditions providing the feed rate of 0.08 mm/rev, whereas the worst surface roughness value (1.8 µm) is discovered at 100 m/min under dry conditions. By taking the average of Ra values of all the cutting conditions, it was observed that the Ra value of the cryo cooling condition decreased significantly to 20% as compared to the dry condition. Similarly, the Ra value of Nano-MQL decreased 7.9% related to MQL only.

In the above figure 5.2, the value of surface roughness becomes best when the speed is lowest (60m/min) while it is inferior when the speed is at maximum (100m/min). In all the lubrication mediums, the value of surface roughness decreases as the speed increases. Dry cutting was superior to the Cryo condition in terms of Ra values. Because, when the average value of Cryo is compared to dry machining, a very effective decrease in the value of Ra is observed. By chilling the cutting area with Cryo, efficiently removes heat from the cutting area. The heat from the cutting tool-chip-workpiece interactions being expelled is anticipated to have a significant role in lowering the Ra values.

Points on the figure 5.3 shows the Average of surface roughness values which was taken for each cooling condition for both feed rates of 0.08mm/rev and 0.12mm/rev. It is observed from the figure below the surface integrity is higher during cryo condition in both feed rates however while comparing both feed rates, better surface quality is achieved at lower feed rate.

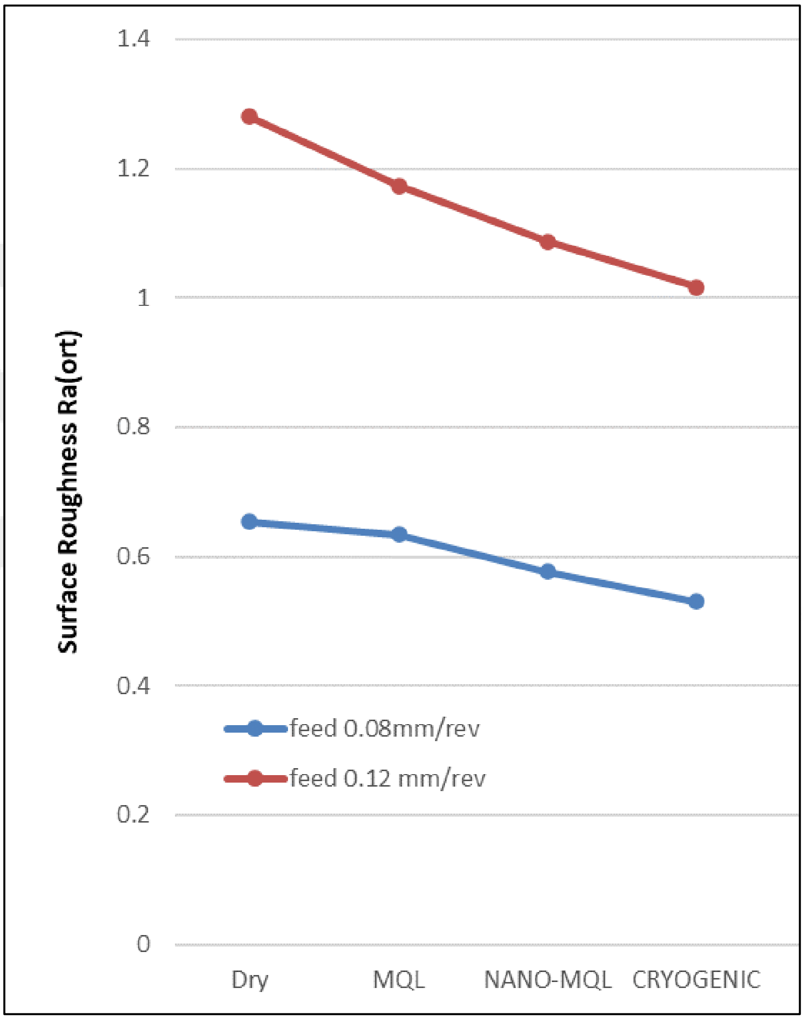


Figure 5.3 Surface roughness variation at each feed rate.

Further, at both feed rate's surface roughness average was taken at each cutting condition. At 60m/min, surface roughness integrity increases with MQL, nano-MQL and cryo. Similar trend has been observed for 80m/min and 100m/min. It is shown in the figure 5.4 that better surface roughness was achieved at 60m/min with cryo cooling condition.

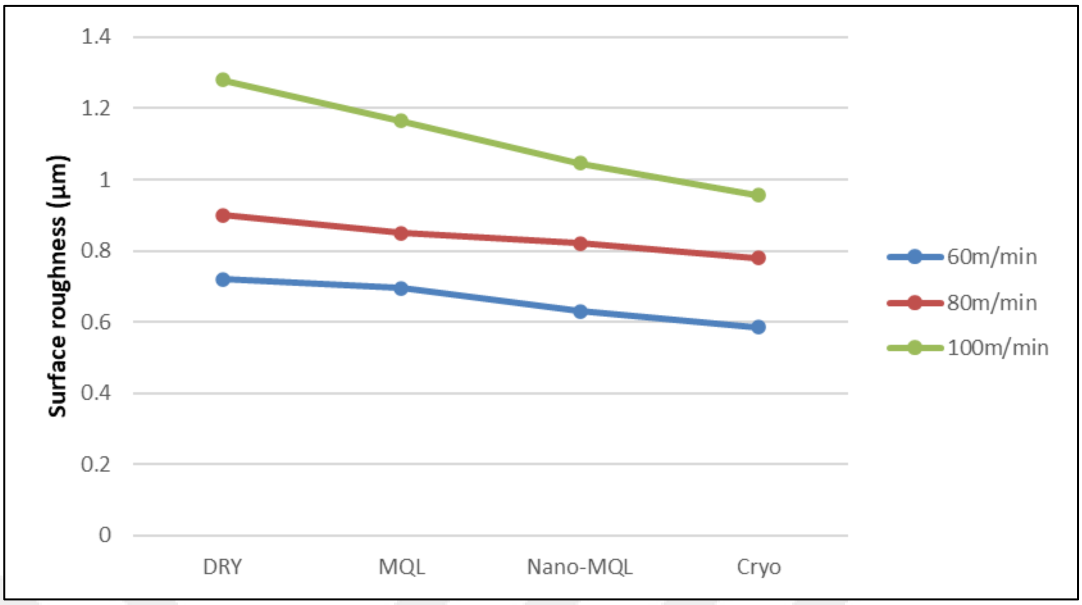


Figure 5.4 Surface roughness averages at each cutting speed.

To study the surface roughness while increasing the cutting speed, following points were observed from the figure 5.5:

- Under dry conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min surface roughness decreased by 20% and 29.68%.
- Under MQL conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min surface roughness decreased by 18.23% and 27%.
- Under nano-MQL conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min surface roughness decreased by 23.17% and 21.53%.
- Under cryo conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min surface roughness decreased by 25% and 18.2%.

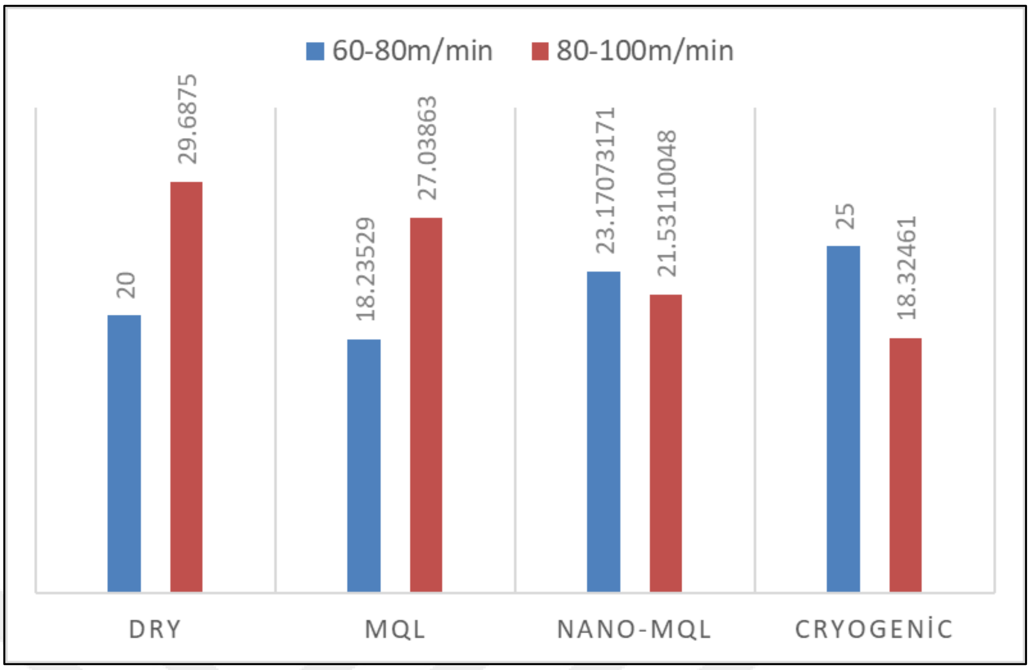


Figure 5.5 Surface roughness variation while increasing cutting speeds.

By comparing MQL, nano-MQL and cryo with dry machining environment, surface integrity was improved by 6.55%, 13.96% and 20.0% respectively.

Compared to the MQL cutting condition, the Cryo cutting condition shows better roughness condition and still provides better roughness quality obtained in the dry cutting at the slowest cutting speed conditions. We can detect a little increase in Ra values when cutting speed is increased. The lowest Ra values were achieved by the cryo chilling condition because it actively lowers the temperature in the cutting zone. MQL helps to reduce friction where the cutting tool, chip, and workpiece come into contact. Under the MQL situation, oil droplets were pushed under pressure into the cutting zone for efficient tribological lubrication performance. As a result of greater lubrication, better surface quality was achieved in NANO-MQL conditions compared to MQL-only environments.

By using methods like MQL and nano-MQL from a broad view, fluid consumption and production costs can be reduced[88]. The cutting zone in MQL is sprayed with a small amount of biodegradable (recycled) oil that has been combined with compressed air. In addition to improving surface quality, this lowers the cutting temperature and cutting tool wear[89]. The cutting fluid employed in the MQL system can be modified to create nanofluids by mixing in nanoparticles such hBN, Al2O3, and MoS2 in certain amounts[56]. The heat created at the cutting spot is evacuated from the environment more effectively because nano-fluids have significant thermal conductivity qualities [90]. According to Cetin et al.[91] and Haq et al. [92],the nano particles in the MQL system produce higher surface quality because they lubricate the cutting zone more effectively. The hBN additive nano-MQL approach produced the best surface roughness results.

After a particular cutting speeds, some researchers found that surface roughness gradually[93]. This incident has a specific cause as well. In actuality, excessive cutting speed increases the machining zone's heat, which is the primary source of tool damage, and the damaged tool has an adverse effect on the surface. On the other hand, when the speed rises, the workpiece begins to rotate around the tool very quickly, which is another factor contributing to the development of uneven surfaces.

5.2. TOOL WEAR

When mechanical, thermal, fatigue and chemical loads are applied during machining operations, tool wear is a notable side effect that results [94]. While cutting difficult-to-cut materials like Inconel alloys, distinct sorts of mechanisms such as abrasion, built-up edges, adhesion, diffusion, etc. were noticed. The highest cutting speed of 100m/min during a dry test resulted in maximum flank wear of 244µm at feed rate of 0.12 mm/rev, according to an analysis of tool wear values as shown in figure 5.6.

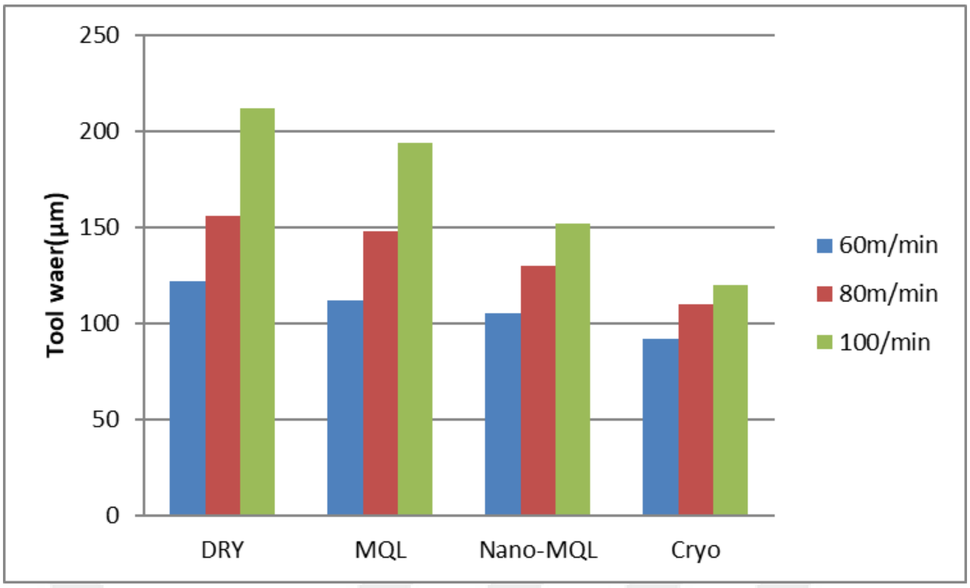


Figure 5.6 Tool wear at feed rate 0.08 mm/rev under various conditions.

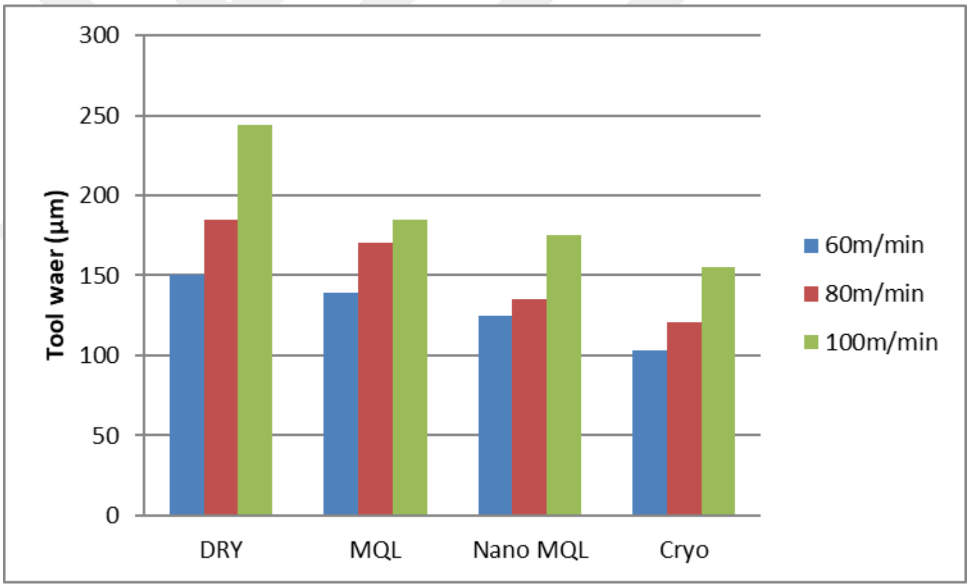


Figure 5.7 Tool wear at feed rate 0.12 mm/rev under various conditions.

The flank wear values for low and medium cutting speeds are 135 µm and 148 µm. Under dry condition cutting speed rose from 60 to 80m/min, provided the feed rate 0.08 and 0.12 mm/rev, yet during this time tool wear increased by 77% and 38% respectively. While in the MQL cutting conditions, at the feed rate 0.08 and 0.12 mm/rev, with the increase in speed 60 to 100m/min the tool wear increased by 70.18% and 24.8% respectively. Similarly, in nano-MQL provided the feed rate 0.08 and 0.12 mm/rev, the tool wear increased by 30.92% and 28.57% respectively when the speed increased from 60 to 100m/min. while in the cryogenic cooling, at the feed rates 0.08 and 0.12 mm/rev the tool wear increased by 23.33% and 33.54% with the increase in speed from 60 to 100m/min. by taking the average values of tool wear in all the cutting conditions and feed rates, the tool wear increased by 24.4% in dry conditions as compared to cryo cooling condition. Similarly, the tool wear increased by 13.29% in MQL as compared to nano-MQL conditions. So, it is observed that by increasing the speed and feed rate, tool wear also increases.

In the figure below 5.8, average of tool wear values which was taken for each cooling condition for both feed rates of 0.08mm/rev and 0.12mm/rev. It is observed from the graph that tool wear is higher during dry and low at cryo condition in both feed rates.

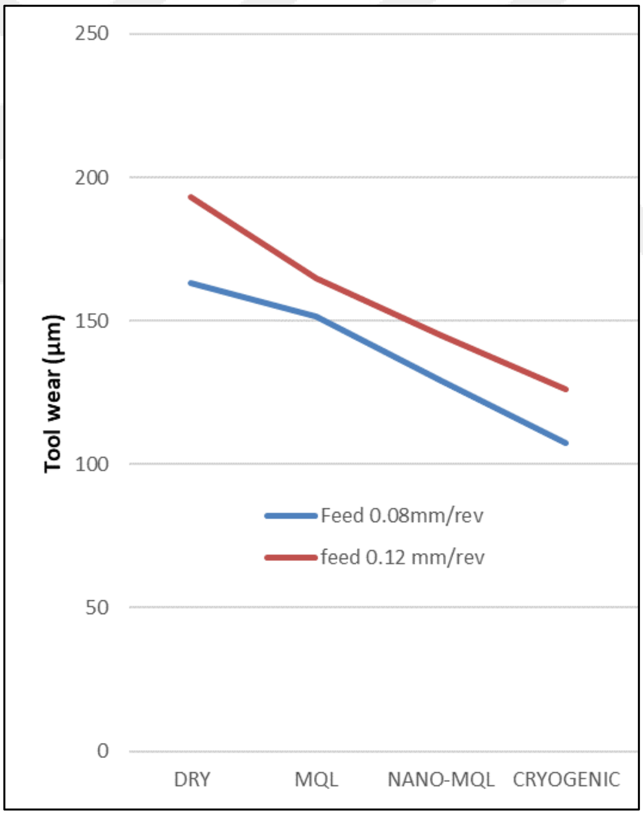


Figure 5.8 Tool wear variation at each feed rate.

In the figure 5.9, both feed rate’s tool wear average was taken at each cutting condition. At 60m/min, tool wear decreases with MQL, nano-MQL and cryo. Similar trend has been observed for 80m/min and 100m/min. It is shown that less tool wear was achieved at 60m/min with cryo cooling condition.

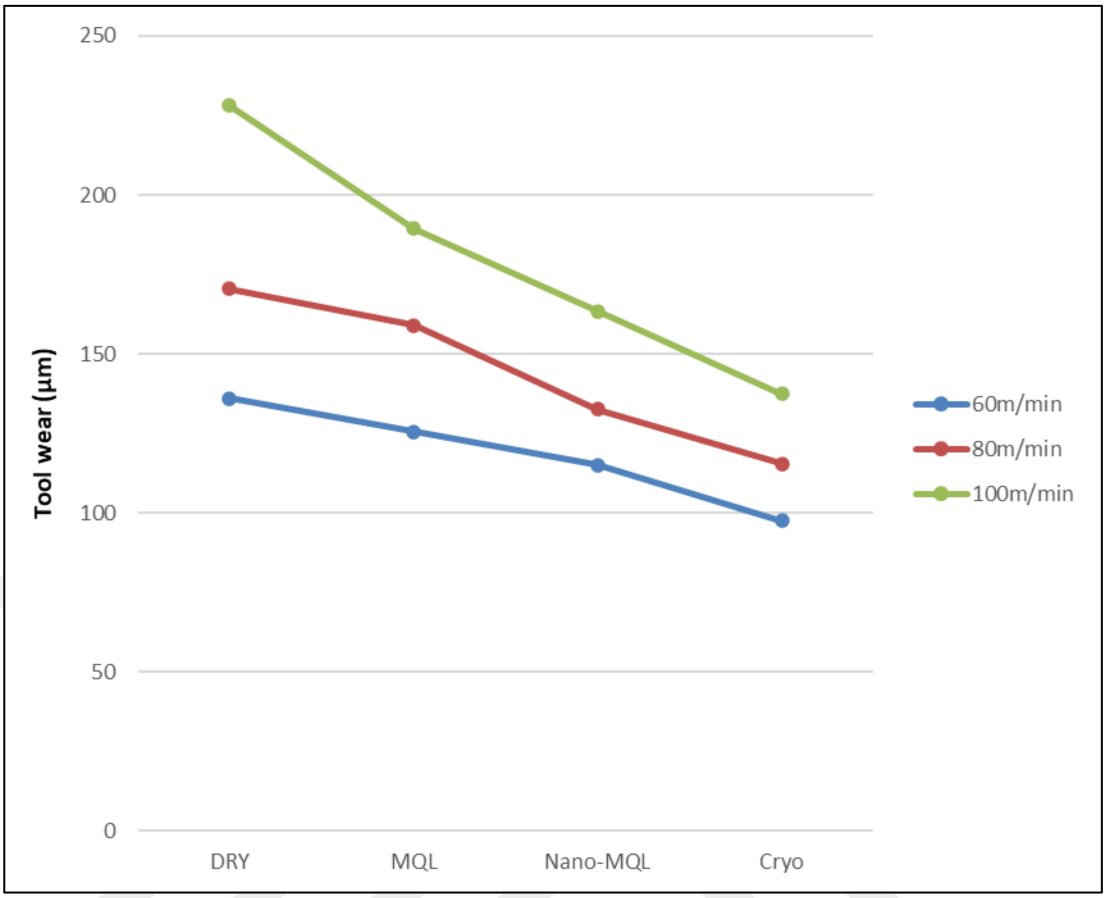


Figure 5.9 Tool wear averages at each cutting speed.

To study the tool wear while increasing the cutting speed, following points were observed from the figure 5.10:

- Under dry conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min tool wear increased by 20.23% and 25.21%.
- Under MQL conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min tool wear increased by 21% and 16%.
- Under nano-MQL conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min tool wear increased by 13.20% and 18.96%.
- Under cryo conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min tool wear increased by 15.58% and 16%.

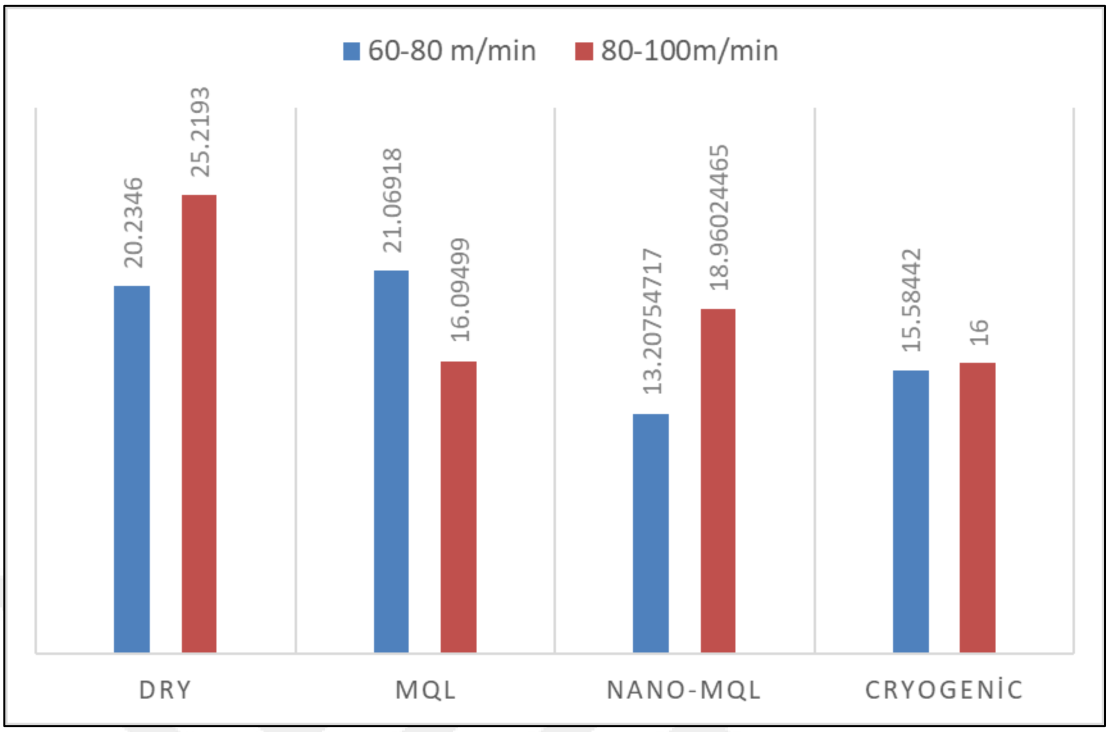


Figure 5.10 Tool wear variation in % while increasing cutting speed.

In the by comparing MQL, nano-MQL and cryo with dry machining environment, tool wear was decreased 11.31%, 23.10% and 34.42% respectively.

All methods of removing metal produce heat due to friction between the chip and tool, chip contact during cutter movement and plastic deformation at the cutting tool tip. Heat is removed from the interface between the tool and the workpiece using cutting fluid. The tools' yield strength is reduced as a result of the cooling process, which also prevents wear from rising above the critical temperature. The ability of coolant to lubricate the tool, workpiece, and chip is another crucial function. One of the most important functions of cutting fluids is to remove the chip from the cutting area, cool it, and stop tiny particles like dust from settling in the liquid and mixing with the air. To avoid deterioration of the completed surface, which postpones tool wear, the cutting area must be routinely cleaned of chips produced during machining. In high-pressure systems, coolant served as a chip breaker because coolant application has an impact on chip formation as well.

The MQL decreased the cutting temperature, enhanced the chip-tool interaction, and maintained the cutting edge sharp, according to Jagatheesan et al.[95] and Gaurav et al.[96]. The study found that the nano-MQL technique was superior to MQL because it is simpler to penetrate the chip-tool interaction zone since the nanoparticles' viscosity is lower[97].

5.3. TOTAL POWER CONSUMPTION

There are various phases to power usage during machining operations. As shown in Figure 5.11 and 5.12, it was discovered that the maximum total power usage under dry testing conditions was 1944 W at the highest cutting speed 100m/min at the feed rate 0.12 mm/rev while the minimum power consumption was 1660W at the feed rate of 0.08 mm/rev under cryo cooling condition. Under dry-cutting conditions, the cutting speed was increased from 60 to 100 m/min, provided the feed rate 0.08 and 0.12 mm/rev, resulting in a 6.79% and 9.87 % increase in power consumption respectively. While in MQL condition, with an increase in cutting speed from 60 to 100 m/min, at feed rates 0.08 and 0.12 mm/rev, the power consumption rises by 6.33% and 6.98% respectively. This increase rate is 5.32% and 6.82% respectively from 60 to 100m/min of cutting speed at feed rates 0.08 and 0.12 mm/rev in nano-MQL conditions. While in cryo cooling conditions, at feed rates of 0.08 and 0.12 mm/rev this power consumption increased to 4.59% and 5.96% respectively with an increase in speed from 60 to 100m/min.

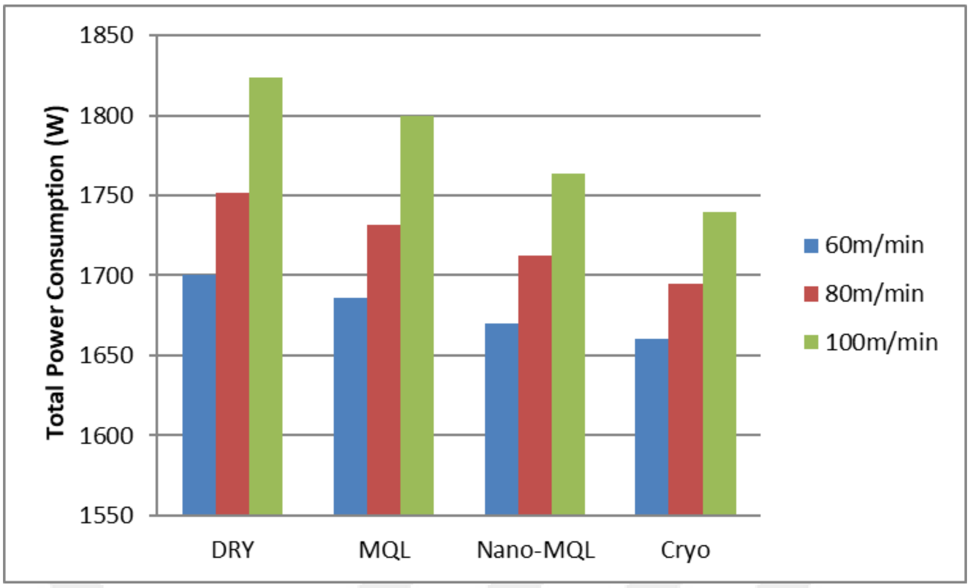


Figure 5.11 Power consumption at feed rate 0.08 mm/rev under various conditions.

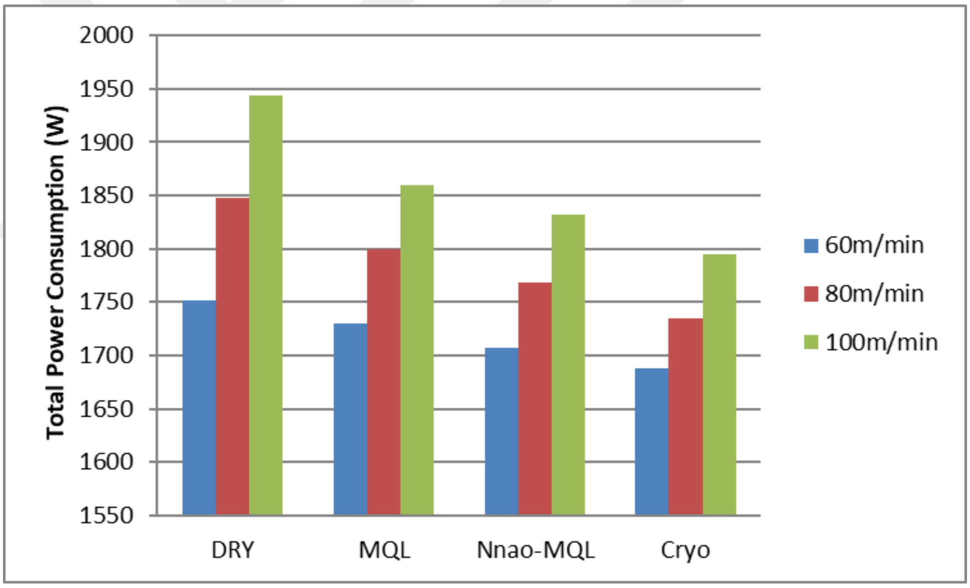


Figure 5.12 Power consumption at feed rate 0.12 mm/rev under various conditions.

In the figure 5.13 shows the average of total power consumption values which was taken for each cooling condition for both feed rates of 0.08mm/rev and 0.12mm/rev. It is observed from the graph that total power consumption is higher during dry and low at cryo condition in both feed rates.

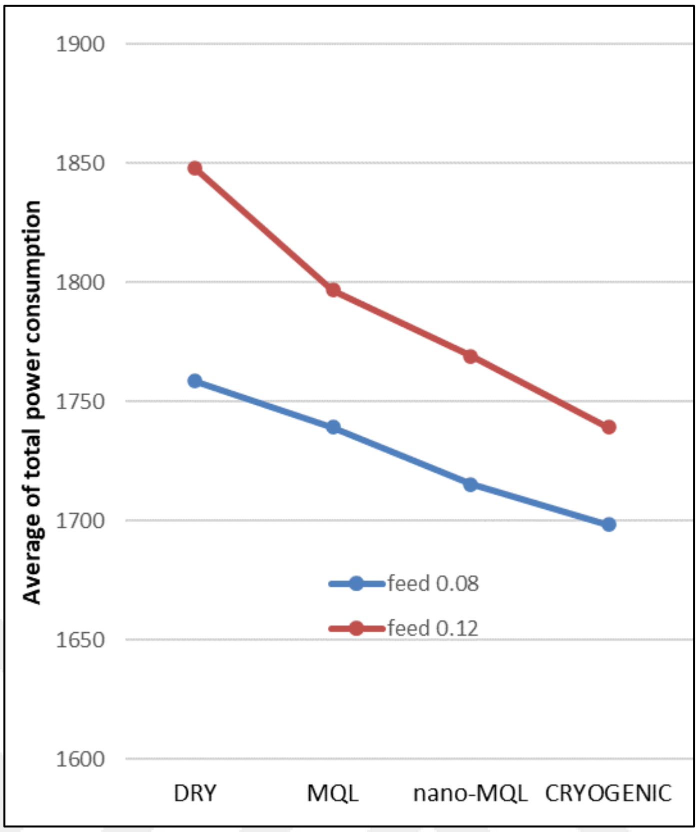


Figure 5.13 Power consumption variation at each feed rate.

In dry conditions, total power consumption was increased by 4.83% when feed rate was increased from 0.08 to 0.12mm/rev. Similarly, for MQL, nano-MQL and cryo total power consumption increased by 3.19,3.03% and 2.35% respectively.

Both feed rate’s total power consumption average was taken at each cutting condition. At 60m/min, total power consumption decreases with MQL, nano-MQL and cryo. Similar trend has been observed for 80m/min and 100m/min. It is shown in the figure 5.14 that less tool total power consumption was achieved at 60m/min with cryo cooling condition.

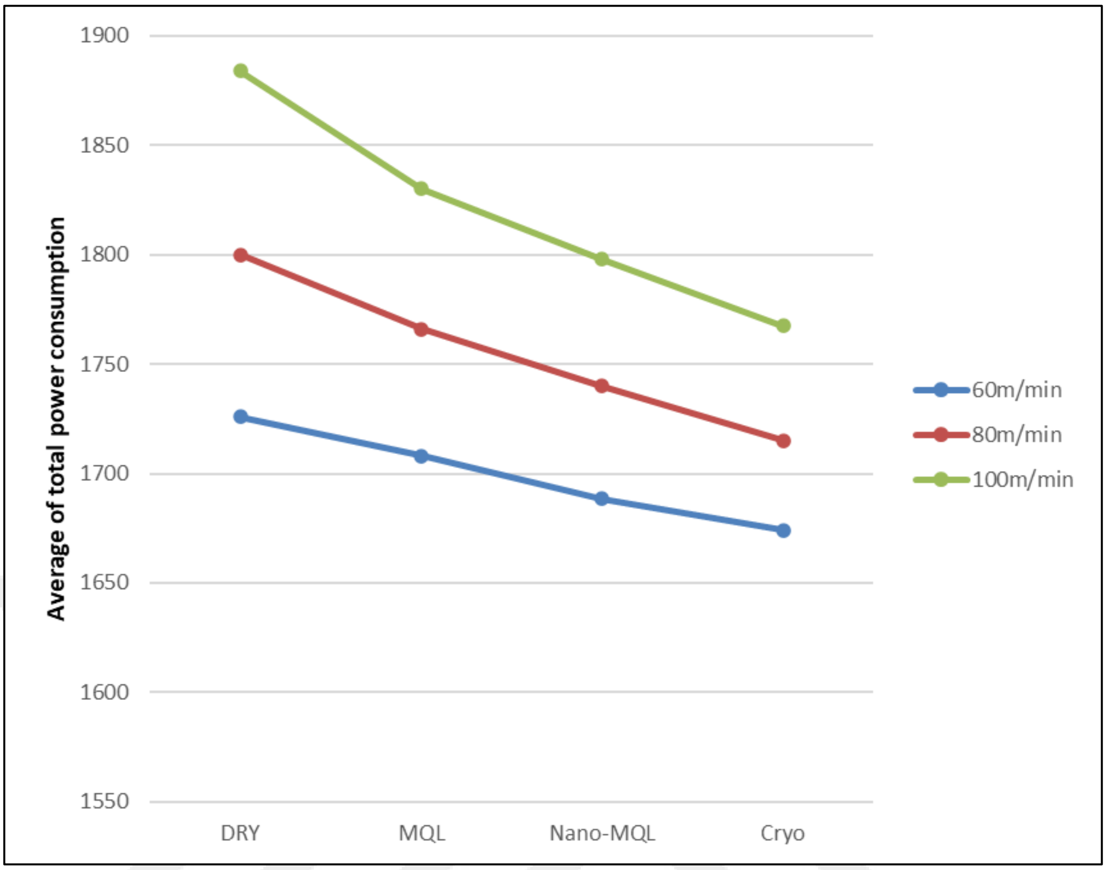


Figure 5.14 Power consumption averages at each cutting speed.

To study the tool wear while increasing the cutting speed, following points were observed from the figure 5.15:

- Under dry conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min total power consumption increased by 4.11% and 4.45%.
- Under MQL conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min total power consumption increased by 3.28% and 3.49%.
- Under nano-MQL conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min total power consumption increased by 2.95% and 3.22%.
- Under cryo conditions, when cutting speed was increased from 60 to 80m/min and 80-100m/min total power consumption increased by 2.39% and 2.97%.

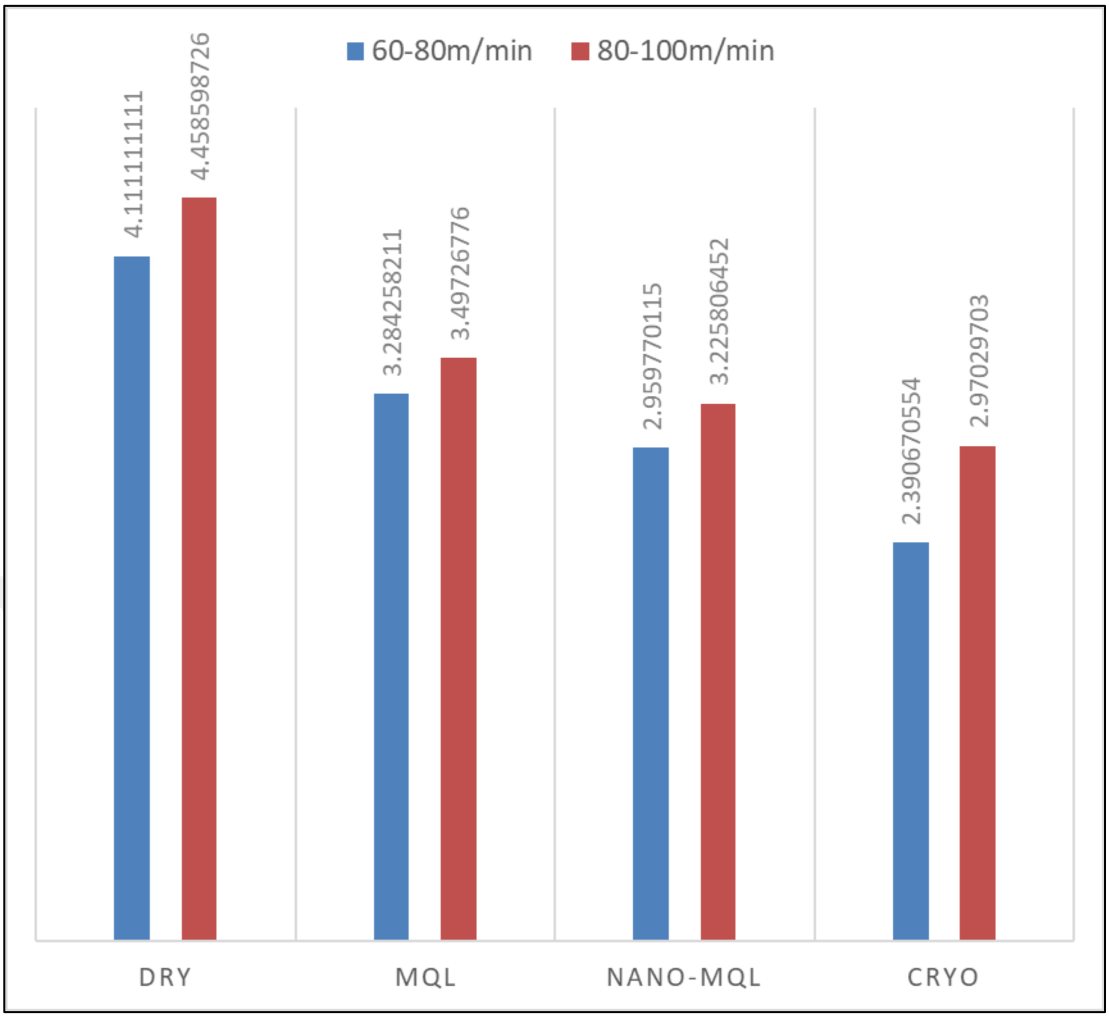


Figure 5.15 Power consumption variation in % while increasing cutting speed.

By taking the average of all the total power consumption values in different machining environments, it is observed from the figure 5.20 that MQL, nano-MQL and cryo with dry machining environment, total power consumption was decreased 1.95%, 3.39% and 4.6% respectively.

The majority of coolants lessen friction, and cryogenic cooling reduces the high temperature in the cutting region, which lowers the power needed to machine a particular material. Not only would this utilize less energy, but less heat would also be produced as a result. The tool life increases, and the work material's surface integrity is maintained when less heat is produced. It is possible to say that the lubrication utilized in the MQL application lessens the contact between the tool and the workpiece, reducing the friction and lowering the power used. Nanoparticles also appear to have greater lubricating qualities and are successful in achieving the lowest power consumption values. Haq et al. [92] and Race et al.[98] indicated that the tool wear has been reduced more when compared to situations where MQL and conventional methods are used separately. As a result, power consumption and surface roughness values were relatively reduced, leading to increased productivity and machinability. On the other hand, Oliveira et al. [99]and Winter et al.[100] highlighted the importance of improving the turning process's machining parameters to reduce the power consumption of the subsystems that support it.

5.4. DISTRIBUTED POWER CONSUMPTION

In the experiment, a significant increase in the machining power was observed with an increase of cutting speed and feed rate. Such behavior was observed under all machining environment conditions like dry, MQL, nano-MQL and cryo. By taking the average values of standby, spindle and machining power, they turned out to be 1560 W, 64W and 134W respectively. The power consumption distributed among these factors is shown in the figure below:

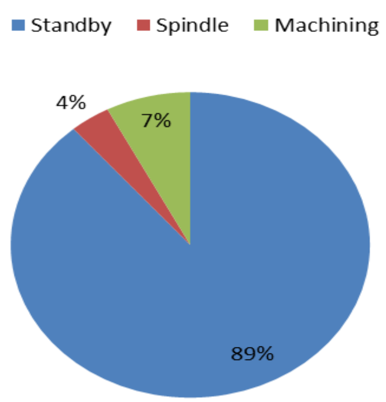


Figure 5.16 Distributed power consumption in an average machining.

The power consumptions of standby, spindle rotor, and linear rotor in a CNC machine tool are also significant for overall power usage during a single machining test, as highlighted in research by Oliveira et al.[99] and Winter et al.[100]. To ensure the sustainability of the machining system, the power consumptions of each subsystem (standby, spindle rotor, and linear rotor) were calculated. It is reasonable to remark that the optimization of machining conditions is so significant in terms of sustainability and costs since it accounts for about half of the total power consumed by a CNC system when considering the impact of changes in machining conditions on power consumption.

5.5 OPTICAL MICROSCOPE IMAGES OF CUTTING INSERTS

Microscopic images of the cutting inserts were observed after the constant 8 minutes machining time. Observation was done at different speed level in comparison to feed rate under the effect of several environments of the machining as seen in Figure 5.17.

It can be observed from figure 5.6 and 5.7, that when Inconel-601 is machined by using carbide inserts under dry, MQL, nano-MQL and cryo environmental conditions, at different cutting speeds, there is a significant change in the tool wear mechanism. Under different cooling conditions, the burning of tool due to excessive heat energy can be easily observed. From the figure 5.6 and 5.7, it is also clear that during machining procedure, flank wear mechanism takes place along with adhesion and built-up edges (BUE) formation. We can say that the real cutting edges cannot cut the tool tips properly, so at this point the previously formed BUE performs as cutting edges. Similarly, when the cutting speed is increased, the temperature due to heat energy rises and tool wear is more prominent. In this situation, cooling conditions such as MQL and nano-MQL may be regarded as better environmental conditions for less tool wear. Similar results were achieved by Gupta et al.[63] while machining 2205-duplex steel.

According to figure 5.6 and 5.7, during dry conditions, when a cutting speed of 60m/min and 80m/min are applied, the tendency of Inconel-601 to harden causes abrasion and adhesion on the outer sides of the cutting. Similar results were observed by Sarikaya, and Gullu and Yildirim et al.[101] during the machining of Waspaloy. The reason for these abrasions and adhesions lies in the fact that Inconel-601 is a very hard metal and is difficult to machine, due to its sticky nature and hardening tendency, it becomes harder when applied stress which results in abrasion at the flank face. Now, if the cutting speed is increased to 80 and 100m/min in dry condition, BUE mechanism is more prominent at both 0.08mm/rev and 0.12mm/rev, the reason behind this is the cutting energy which is built up and further converted into heat energy and the material becomes soft and adheres to the cutting edges. It was also observed by Mohanty et al. [102] when they were machining some aerospace material.

Under dry condition, it is seen the maximum abrasion and adhesion while comparing to other cooling conditions. BUE is also very prominent in the dry conditions. However, MQL and Nano-MQL showed us better results in this regard, as the BUE is becoming less prominent, especially at the lower feed rate of 0.08 mm/rev. In case of cryo cooling, it is observed that abrasion and Adhesion is very prominent in both feed rates, 0.08 mm/rev and 0.12 mm/rev. This tool wear seems more prominent, due to lack of lubrication effect in the cryo cooling environment system.

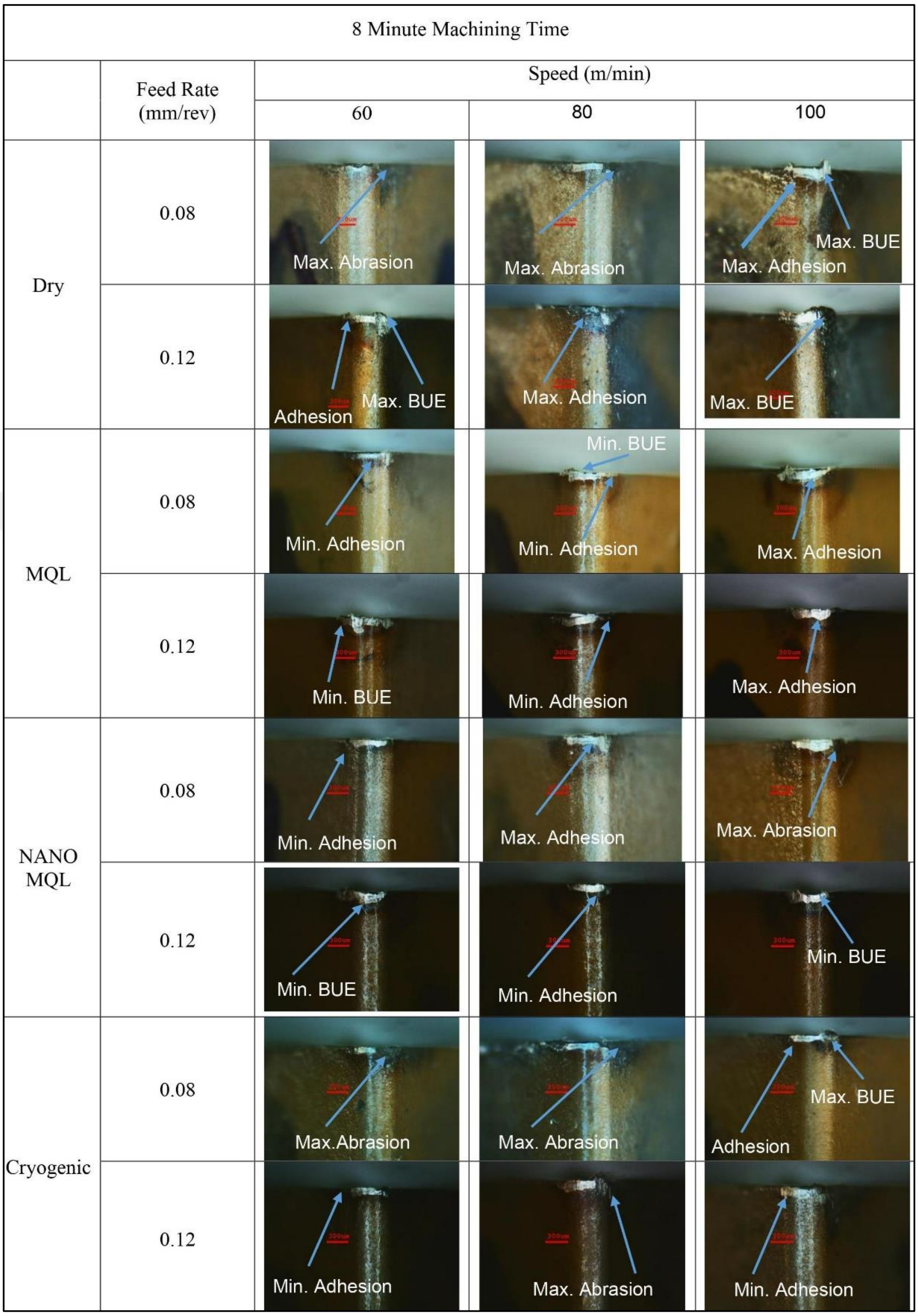


Figure 5.17 Optical microscope images of cutting inserts .

PART 6

CONCLUSION

Inconel 601 rollers used in turning operations were machined using coated carbide tools under dry, MQL, cryogenic, and hybrid nano + MQL conditions environments. The conclusions are summarized in the section below.

- Surface roughness values were significantly influenced by cooling conditions, and the machining circumstances changed the average values of surface roughness. Lower Ra surface roughness values were observed during cryo cooling machining conditions because cryo significantly helps to reduce the temperature in the cutting area. The lowest Ra value was 0.97µm in cryo at feed rate of 0.08µm and cutting speed of 60m/min and maximum Ra value was 1.8µm in dry at feed rate of 0.12µm and cutting speed of 100m/min.

- When cutting Inconel 601 alloy, tool wear is a major concern. Cooling conditions cause a significant shift in the readings. As compared to dry conditions, average values of tool wear in MQL, nano-MQL and cryo have shown significant improvements in their properties by 11.31%, 23.10% and 34.42% respectively. The lowest tool wear was 92 µm in cryo at feed rate of 0.08µm and cutting speed of 60m/min and maximum value was 24µm in dry at feed rate of 0.12µm and cutting speed of 100m/min.

- It is observed that the lowest total power consumption was 1660W at the feed rate of 0.08mm/rev and cutting speed of 60m/min. Nevertheless, the maximum total power was 1944W at the feed rate of 0.12mm/rev and cutting speed of 100m/min. When average of total power consumption in dry condition is compared to MQL, nano-MQL and cryo conditions, significant improvements of 1.95%, 3.39%, and 4.68% respectively are observed.

- Because of cryo encouraging impact at the cutting zone, cryo reduces power levels. It lessens the cutting forces, which has the effect of using less power to remove the chips from the resistive body.

- Based on results, cryo provides efficient cooling environment conditions for machining however as Cryo provides better cooling and MQL provides better lubrication conditions during machining so in order to get better surface roughness along with less wear and minimum power consumption, hybrid cryo + MQL cooling/lubrication condition could be considered for future research.

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RESUME

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