



Review On Machining Inconel 718 Using Cryogenically Treated Inserts And Cryogenic Cooling

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Abstract: Inconel 718 is a nickel-based superalloy which is more commonly used in aerospace, marine, and chemical applications due to its mechanical strength, oxidation and corrosion resistance, and stability at high temperatures. However, these same characteristics contribute to rapid tool wear, high cutting temperatures, bad surface finish, and rising costs of machining during cutting processes. This review focuses on the effect of cryogenically treated inserts and cryogenic cooling during the turning of Inconel 718.

Cryogenic treatment basically increases hardness, toughness, and wear resistance of cutting inserts through deep cooling and microstructure refinement. Cryogenic cooling using liquid nitrogen generates an effective minimal cutting zone heat along with thermal softening of the tools and suppression of built-up edge formation.

Results of experimental works carried out so far demonstrates that there was significant improvement in tool life and surface integrity with reduced cutting forces due to the combination of cryo-treated inserts and cryogenic cooling. These results show the benefit that might be obtained by cryogenic strategies to improve the machinability of Inconel 718, yielding sustainable and cost-effective manufacturing processes in high-performance applications.

Index Terms Inconel 718, Superalloy, Cryogenics

I. INTRODUCTION

Nickel-chromium (Ni-Cr) alloys are one of the types of high-performance materials that enjoy great corrosion resistance, high-temperature strength, and oxidation resistance. The applications of these materials cut across numerous industries like the aerospace industry, power generation industry, chemical process industry, and marine industry. Inconel used commonly to form critical parts in defence, aerospace, and nuclear applications [1]. Owing to very good properties related to corrosion and oxidation resistance, Inconel X-750 which is a nickel-based super alloy retains much strength normally up to about 700 °C, whereas in some cases, it is also known to perform well up to 980 °C. Its durability qualifies it for applications involving high-temperature as well as cryogenic applications, including rocket thrust chambers [2]. Nickel alloys can withstand extremely high temperatures, hence the metal choice for components such as gas turbines, marine and airplane engines [3]. Inconel is used in turbines and engines due to low thermal expansion coefficient and the ability to maintain strength at high temperatures [3].

A challenging task would be the machining of nickel-based alloys due to the low thermal conductivity and also the work hardening of the nickel-based alloys, creating more heat and also stress levels in the work zone. All of these factors make it difficult to machine and also enable efficient machining processes [4]. Inconel possesses a great degree of strength, excels in hot hardness, high impact strength, and possesses excellent corrosion resistance. These properties, along with the work-hardening characteristic, make Inconel difficult to machine; other contributing factors to this difficulty include poorer thermal conductivity (11.2 W/mK) and built-up edge formation. [5]. Machining Inconel creates various problems, most of which are attributed to the generation of heat during cutting operation, high cutting forces producing residual stresses, chip deformation and removal problems, as well as poor surface quality associated with machining [6]. The worn-out tool produces a poor surface finish, affecting the quality of the finished machined component

[7,8]. The temperature can rise very high at the interfaces of the materials during machining, especially at speeds higher than normal. The surface integrity and overall efficiencies of metal cutting operations in the aerospace industry play a significant role and are most affected by excessive heat generation and by the formations of wear [9].

Techniques related to cooling and lubrication systems are being invented for enhanced machining performances of superalloy materials such as cryogenic methods, a most recent development among them, which optimized the effects through proper management of heat produced during their machining [10,11]. Minimum Quantity Lubrication (MQL) machining produced comparable or sometimes better results than those attained in traditional wet machining (an emulsion). In MQL, air is blended with a very small oil volume, resulting in the formation of a very fine mist cloud that is directed toward the cutting zone. In the vicinity of the tool/workpiece interface, these tiny droplets create a tribo-film thereby minimizing friction and tool wear [11]. Wear resistance required enhancement of cutting inserts to improve machining performance.

Another method of enhancing wear resistance is cryogenic treatment applicable for all types of cutting inserts like HSS tools, carbides, ceramics, CBN, and PCBN as well as coated inserts [12]. Cryogenic heat treatment has a stabilizing effect on the carbides that are embedded in the metal matrix since they are more stable. It also changes the cobalt phase or crystal structure in the metal matrix to better withstand different loads during cutting operations [13]. Cryogenic treatment is an eco-friendly procedure that assists in increasing tool life by enhancing the resistance of cutting tools to abrasive wear during machinability. This technique helps enhance performance and is eco-friendly to manufacturing processes [14,15]. Cryogenic treatment significantly prolongs inserts cutting life by minimizing notching, chipping, plastic deformation, and wear, which are some of the factors most responsible in cutting applications. DCT tools exhibit lower flank wear with high cutting speeds and feed rates as compared to untreated ones while machining Inconel 718. This condition tends to improve the overall performance and maximize the usage of the tool [16,17].

Machining of heat-resistant alloys is best facilitated by applying cooling and lubrication methods. These methods help to dissipation of heat from the cutting zone and provide sufficient lubrication to minimize friction at the chip-tool and workpiece-tool interface, thus enhancing tool life and machining efficiency [3]. Selecting the right cutting fluid is most important for the maintenance of surface quality by dissipating heat from the cutting zone. Cooling and lubrication prevent thermal damage, reduce tool wear, and enhance overall machining performance [5].

During Machining, the choice of machining condition significantly affects tool wear, surface finish, cutting forces, temperature, environmental impact, and machining cost.

1.1 Dry machining condition

Dry machining is a cutting process that does not utilize any coolants and lubricating media during its operation. The method depends on optimized cutting parameters, advanced tool materials, and coatings to minimize friction and heat generation. Dry machining is considered as an eco-friendly process in that it does not require the use of cutting fluids, thus eliminating waste and disposal costs. However, for difficult-to-cut alloys like Inconel 718, dry machining is not commercially desirable since it will cause excessive tool wear, increased cutting temperatures, and very poor surface finish making it not feasible for industrial applications [11].

1.2 Wet machining condition

Wet machining is that process of machining in which the machines are worked by supplying cutting fluids. The secondary objective of lubricants, in addition to obtaining more efficient and superior material removal, is to dissipate heat and prevent friction with respect to the cutting tool and workpiece. Besides all these, the lubricant gets rid of the chips produced. The method has great potential for improving surface finish as well as lasting longer in terms of tooling. Wet or flood coolant is commonly used for lubrication and cooling in milling operations in the metal cutting industry. But it has some adverse effects both on the machinist and the environment [9].

1.3 Minimum quantity lubrication machining condition

MQL (Minimum Quantity Lubrication) machining is an advanced technique of machining using miniature application of lubricants (primarily in the form of aerosols or mists) unlike the traditional methods of flood coolant usage. This helps to have the features of cooling and lubrication with a minimum application of cutting fluid. The Minimum Quantity Lubrication (MQL) technique delivers a small quantity of cutting fluid to the cutting area as an oil mist. Despite its effectiveness in reducing friction and providing lubrication, the ability of MQL to dissipate heat from the cutting zone is poor and most often results to high tool wear and thermal damage during high-temperature machining applications [3]. The usage of minimum quantity lubrication (MQL) is an economically viable machining process. It is an effective means of delivering a fine

mist of lubricant into the cutting zone for sufficient lubrication. Because high-pressure mist propels the lubricant droplets to interface penetrate the workpiece-tool, there will be less heat and friction to improve tool life with superior surface finish [4]. The application of Minimum Quantity Lubrication (MQL) will be best under low cutting speeds as it helps in heat dissipation and reduces friction. However, for high cutting speeds, MQL will be less effective for the machining of Inconel 718 as it fails to dissipate heat from the tool, leading to an increase in tool wear and a poor surface finish [5].

II. Cryogenic machining condition

Cryogenic machining, a modified cutting technique using cryogenic fluids such as liquid nitrogen or liquid carbon dioxide to cool the cutting zone, offers high-performance machining on high-temperature alloys such as Inconel 718, titanium alloys, and hardened steels, where ordinary cooling is insufficient. Cryogenic cooling significantly extends tool life across various machining conditions when compared individually with dry or wet machining during finishing operations [2]. Cryogenic machining uses liquid nitrogen (LN₂) as an alternative to common oil-based cutting fluids for cooling and lubrication during machining. The very low boiling point of LN₂ at -196°C causes it to take up greater heat and prevents tool wear and thermal deterioration. This quality makes it very suitable for machining heat-resistant alloys such as Inconel 718 and titanium. [3,4,8]. Cryogenically, LN₂ is the common coolant used due to its extremely low temperature. Liquid nitrogen (LN₂) does not take part in any interaction with cutting tool materials or coatings, hence, does not cause damage to the cutting tool. It is an eco-friendly coolant since it does not generate any toxic fumes or residues as compared to oil-based coolants, as well as avoiding health concerns, such as skin irritation and breathing problems, which makes it a viable option for workplace safety. It has a melting point of -210.01°C and a boiling point of -195.79°C. The gas makes up 78% of the air; it is colourless, tasteless, odourless, and non-toxic. It thus finds extensive use for Machining and it doesn't affect the worker [12].

2.1 Cryogenic minimum quantity lubrication machining condition

Cryogenic Minimum Quantity Lubrication (CMQL) is a sophisticated cooling and lubrication method used in machining that combines Minimum Quantity Lubrication (MQL), which is a thin mist of lubricant, with cryogenic cooling, which uses liquid nitrogen (LN₂) or carbon dioxide (CO₂). Particularly for hardened steels, titanium alloys, and Inconel 718—materials that are challenging to cut, this technique is expressly intended to increase tool life, surface quality, and machining efficiency. CMQL, a recent advancement in eco-friendly manufacturing, enhances productivity while preserving environmental sustainability. It ensures effective heat dissipation and reduced friction by combining cryogenic cooling with micro-lubrication. In addition to reducing waste, CMQL machining enhances surface quality, which makes it perfect for precision machining [4].

2.2 Cryogenic treatment to the inserts

Cryogenic treatment is a process in which cutting tool inserts are subjected to extremely low temperatures—primarily using liquid nitrogen at -196 °C, to increase their hardness, toughness, and wear resistance. Such treatment is typically used for improving the performance of machining operations on carbide, high-speed steel (HSS), and ceramic cutting inserts. Deep Cryogenic Treatment (DCT) is an eco-friendly method that uses low temperatures (-196°C with liquid nitrogen) to improve the performance and lifetime of cutting tools. Deep Cryogenic Treatment improves tools mechanical properties, resistance to wear, and thermal stability [2,5,9]. Cryogenic treatment is employed for further enhancement of the machining property by altering the metallurgical characteristics of the tool materials. It improves mechanical strength, wear resistance, and durability of the tools which finally leads to high performance and longer life of the tools [5,9,12]. Cryogenic treatment is a low-temperature heat treatment aimed at enhancing the tool life of carbide cutting tools. This technique imparts hardness, makes them resistant to wear, and gives them strength by altering the metallurgical properties of the tool [13].

III. Cryogenic treatment process

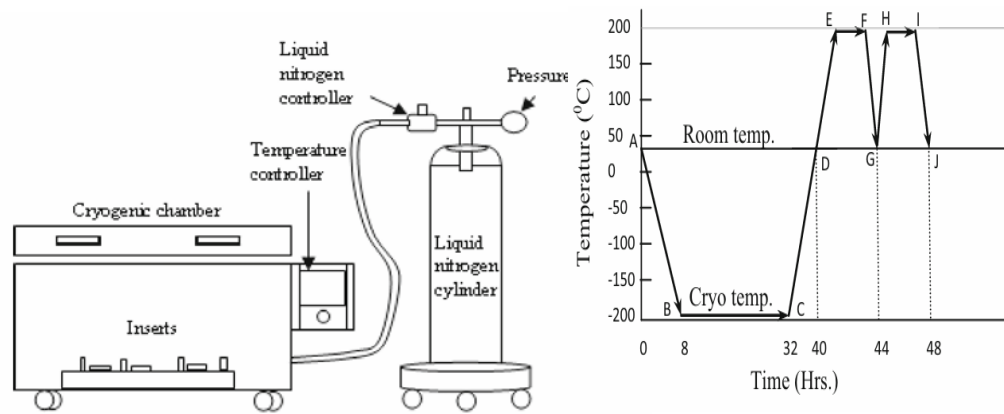


Fig.1: Schematic of the cryogenic system (left) and deep cryogenic treatment cycle (right) [5].

Cryogenic treatment is a widely adopted process to improve the performance of cutting tools, particularly carbide inserts. The treatment involves cooling the material to extremely low temperatures, ranging from -70°C to -196°C , depending on the specific requirements. Variations in the treatment cycle, including temperature and duration, significantly influence outcomes such as tool life, wear resistance, and surface quality. Deep cryogenic treatment (DCT), which cools the material to -196°C , has been found particularly effective in enhancing wear resistance. However, tempering after the cryogenic process is essential to alleviate the internal stresses developed during cooling. To prevent thermal shock and potential damage to the material, the cooling rate is carefully controlled at 0.5°C per minute, requiring around 8 hours to reach -196°C . Once this temperature is achieved, the material is held (soaked) at the same temperature for 24 hours. Gradual warming back to room temperature over the next 8 hours completes the cryogenic cycle, which takes approximately 40 hours in total. Following the cryogenic cycle, tempering is performed to stabilize the material. The tempering process involves heating the material to $+196^{\circ}\text{C}$ within 1 hour, holding it at this temperature for 2 hours, and then cooling it back to room temperature. This tempering cycle is repeated to ensure complete stress relief. The combined cryogenic and tempering process takes about 48 hours [5,14]. Tempering at 200°C was also found to be beneficial following cryogenic treatment. The SEM analysis and chemical analysis of the chips confirmed the presence of diffusion wear. This proves that transforming any remaining austenite into martensite would additionally help increase wear resistance [2].

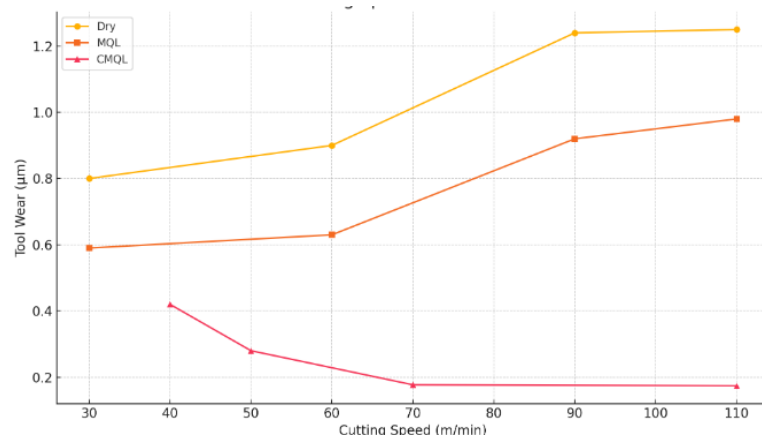
of five years. The time series monthly data is collected on stock prices for sample firms and relative macroeconomic variables for the period of 5 years. The data collection period is ranging from January 2010 to Dec 2014. Monthly prices of KSE -100 Index is taken from yahoo finance.

IV. CLASSIFICATION OF INCONEL ALLOY

Grade	Essential characteristics	Applications
Inconel 600	Oxidation resistance, excellent weldability	Chemical processing, nuclear reactors
Inconel 601	High-temperature stability, corrosion resistance	Furnace components, gas turbines
Inconel 625	Superior corrosion and fatigue resistance	Marine, chemical, and aerospace industries
Inconel 718	Precipitation-hardened, high creep resistance	Aerospace, gas turbines, and nuclear reactors
Inconel 690	Exceptional resistance to aqueous corrosion	Nuclear reactors, heat exchangers
Inconel X-750	High strength, creep resistance	Springs, gas turbines, and aerospace hardware

Table 1 - Classification of Inconel alloys

4.1 Effect on Tool wear



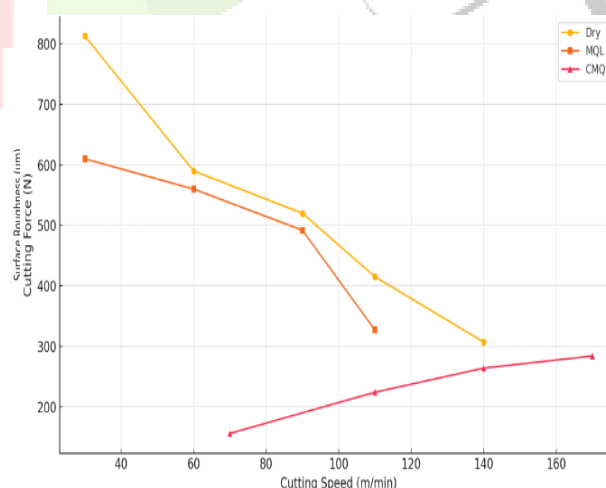
Cutting speed v/s Tool wear Under Different conditions [4,5,14]

Machining of Inconel requires strong, wear-resistant tools due to its high shear strength, work-hardening tendency, and abrasive nature. Fine carbides in its microstructure accelerate tool wear, while low thermal conductivity causes excessive heat at the cutting interface. This heat, along with built-up edge formation, leads to rapid tool wear and shorter tool life. To overcome these challenges optimized machining parameters and specialized cutting tools must be used.

Goran Jovičić et al, conducted experimental evaluation of tool wear and surface roughness during dry turning of Inconel 601 with PVD and CVD inserts. The finding shows that CVD-coated cutting insert without wiper geometry showed maximum wear. The PVD-coated with TiAlN+TiAlN insert with wiper geometry experienced the least wear [1]. Ganesh Shete et al, conducted experiments on the effect of cutting parameters on various output responses for cryo-treated Inconel X750 alloy. The maximum tool wear reported was 0.425 mm with a cutting speed of 55 m/min, a feed of 0.06 mm/rev. The minimum wear was 0.215 mm and was achieved at a cutting speed of 35 m/min, a feed of 0.02 mm/rev [2]. Navneet Khanna et al, conducted experiments to evaluate the tool wear, energy consumption, and surface roughness during turning of Inconel 718 using sustainable machining technique. Dry turning exhibited an increased rate of wear on a tool which failed after 150 mm of cutting. Cryogenic turning led to the lowest tool wear and increased tool life by 133% as compared to dry turning [3]. Venkat Pradeep Allu et al, conducted experiments to analyse the performance of cryogenically treated plus tempered carbide inserts in turning of Inconel 718 using cryogenic minimum quantity lubrication cooling technique. CMQL gave the best tool wear performance, providing good cooling and lubrication, thereby reducing tool wear. Dry machining has produced the worst tool wear, as it used no lubrication at all [4]. Yogesh V. Deshpande et al, conducted experiments to evaluate the performance of cryogenic treatment of tool and minimum quantity lubrication for machinability improvement in the turning of Inconel 718. The lowest tool wear was discovered under Minimum Quantity Lubrication with Cryogenically Treated Inserts (MQL-CT). The tool wear was highest in Dry Cutting with Untreated Inserts due to increased friction and heat in disparate passages. Moderate wear rates were recorded for Dry Cutting with Cryogenically Treated Inserts and Minimum Quantity Lubrication with Untreated Inserts (MQL) [5]. Vincenzo Tebaldo et al, conducted “Eco-friendly” turning of Inconel 718. Results show that, from all cooling techniques, cryogenic cooling resulted in maximum tool wear, wet cooling recorded the lowest value. Thus, wet cooling resulted in better efficiency over lower amounts of tool wear [6]. F. Pusavec et al, analysed surface integrity in cryogenic machining of nickel-based alloy—Inconel 718. The dry machining conditions inflicted the maximum wear of the tool owing to the thermal generation and softening of the tool edge. Least tool wear occurred in cryogenic cooling conditions where liquid nitrogen severed the thermal effects and prolonged the tool life [7]. Sana Chaabani et al, analysed surface integrity when machining Inconel 718 using conventional lubrication and Carbon Dioxide coolant. In CO₂ cooling conditions, the maximum tool wear was recorded with a flank tool wear of 0.14 mm after machining. On the opposite end, conventional wet lubrication exhibited the lowest tool wear with a flank tool wear of 0.12 mm [8]. R Anburaj et al, conducted experiment “Influences of cryogenic CO₂ and LN₂ on surface integrity of Inconel 625 during face milling”, Maximum tool wear was found with LN₂ cooling at 0.6 mm/rev feed and 764 rpm spindle speed, encompassing edge chipping, flank wear, and notch wear. Minimum tool wear is recorded for CO₂ cooling at a feed rate of 0.2 mm/rev and a spindle speed of 509 rpm, without any wear except for flaking and a little bit of edge chipping [9]. A. H. Musfirah et al, conducted investigation to Evaluate the effect of cutting parameters on cutting zone in cryogenic high-speed milling of Inconel 718 alloy, under dry machining condition, tool wear was observed at its peak due to the

generation of too much friction and heat at the cutting zone, whereas tool wear has been significantly minimized with cryogenic machining, with heat transfer reduced up to 70%, resulting in minimal tool wear [10]. SenolSirin et al, conducted investigation on Performance of cryogenically treated carbide inserts under sustainable cryo-lubrication assisted milling of Inconel X750 alloy, using an uncoated tool under LN₂ cooling resulted in the highest tool wear of 0.461 mm, the lowest tool wear of 0.138 mm was observed with a TiAlN-coated tool under MQL + LN₂ cooling, which reduced wear by 70.1% compared to the uncoated tool [11]. S. Thamizhmanii et al, conducted experiment to Evaluate Performance of deep cryogenically treated and non-treated PVD inserts in milling. The tool wear was at its peak i.e., 0.60 mm with the non-cryogenic-treated PVD, the lowest tool wear was found with cryogenic-treated PVD inserts, thus proving better wear resistance and tool life [12]. Bilal Kursuncu et al, conducted experiment to for the Improvement of cutting performance of carbide cutting tools in milling of the Inconel 718 superalloy using multilayer nanocomposite hard coating and cryogenic treatment, uncoated carbide cutting tools exhibited the highest tool wear in a flank wear of 0.2 mm. cryogenically treated nanocomposite TiAlSiN/TiSiN/TiAlN-coated carbide tools showed the least tool wear as it shows wear that is 29% better than untreated tools [13]. Mahir Akgün et al, conducted experiment for Optimization of Cutting Parameters Affecting Surface Roughness in Turning of Inconel 625 Superalloy using Cryogenically Treated Tungsten Carbide Inserts, the highest tool wear coincided with a cutting speed of 90 m/min at feed rate of 0.25 mm/rev with untreated tungsten carbide inserts, which functioned for a prolonged period and resulted in increased wear on the cutting tool. The least tool wear occurred at a cutting speed of 150 m/min and feed rate of 0.1 mm/rev, using tungsten carbide inserts treated at -196°C [14]. S Thamizhmanii et al, conducted experiment to Evaluate the Surface Roughness and Tool Wear on Cryogenic Treated CBN Insert on Titanium and Inconel 718 Alloy Steel, at low feed rates (0.05 mm/rev) and higher cutting velocities (50 m/min), flank wear was seen to be maximum during the machining of Titanium alloy. On the other side, Inconel 718 showed less flank wear at a depth of cut of 1 mm, as compared to deeper cuts at 0.50 and 0.75 mm. The possible crater wear depth was less and was found to be more uniform across Inconel 718 [15]. Hui-Bo He et al, conducted experiment to Evaluate the Effect of Deep Cryogenic Treatment on Machinability and Wear Mechanism of TiAlN Coated Tools during Dry Turning. during dry turning of AISI 5140 steel, the highest tool wear was observed in uncoated tools, the least tool wear occurred with the deep cryogenically treated (DCT) tools, gives about a 30% increase in tool duration compared to non-cryogenic treated (NCT) tools [16]. A. Palanisamy et al, conducted experiment to Optimization of Turning Parameters of Machining Incoloy 800H Superalloy Using Cryogenically Treated Multilayer CVD-Coated Tool, at a cutting speed of 35 m/min, feed rate of 0.06 mm/rev, and depth of cut of 0.5 mm, maximum tool wear was experienced with increased flank and crater wear. The minimum tool wear at a cutting speed of 55 m/min, feed rate of 0.06 mm/rev, and depth of cut of 1 mm, with the use of a cryogenically treated multilayer CVD-coated tool [17].

4.2 Effect on surface quality



Cutting speed v/s surface Roughness under Different conditions [5,10,14]

The PVD-coated insert possessing wiper geometry generated maximum surface quality with minimum roughness. The CVD-coated insert without wiper geometry has exhibited the lowest surface quality with the highest roughness [1]. The roughest surface recorded was 1.485 μm roughness at a cutting speed of 35 m/min, 0.06 mm/rev feed, and a depth of cut of 0.5 mm. Conversely, at a cutting speed of 55 m/min, 0.02 mm/rev feed, and 1 mm depth of cut, the smoothest surface had a roughness of 0.720 μm [2]. The smoothest surface was obtained with cryogenic turning, enhancing the Ra value by 20% over the value of wet turning, and 37% over that of dry turning. Dry turning had the highest surface roughness due to the

rapid wear of the tool and the uneven formation of the chips. It was also found that wet turning performed better than dry turning, but not as well as cryogenic turning [3]. CMQL provided better surface finish having the least roughness. In the dry machining operation, the surface finish is rough because there is higher wear of cutting tools together with improper chip control. MQL did better than dry machining, however it did not perform as good as CMQL [4]. MQL-CT attained the smoothest surface, clearly as lubrication plus reduced tool wear secured a stable cutting process. The grossest surface was produced in Dry machining with the combination of high friction, tool wear, and vibration. The intermediate surface roughness values were achieved with MQL and Dry-CT [5]. Under cryogenic cooling condition, the highest surface roughness (S_a) was found to be $0.4555 \mu\text{m}$ due to excessive cutting-edge fracture. In contrast, the smoothest surface was produced with wet cooling due to a lubricoolant that reduced heat accumulation, with S_a values in the range of $0.2509 \mu\text{m}$ [6]. In dry machining conditions, increased friction and uneven tool wear lead to a rough surface finish and reduced surface quality, Cryogenic lubrication (Cryo + MQL) gives the finest surface finish since cooling/lubrication leads to less tool wear and better finish [7]. Under CO_2 cooling, there was higher surface roughness because the lower temperature encouraged strain hardening near the surface. In contrast, conventional wet lubrication results in a smoother surface due to better heat dissipation [8]. CO_2 cooling at a feed rate of 0.2 mm/rev and spindle speed of 509 rpm gave the best surface finishing (best roughness) with few grooves and feed marks. Conversely, the worst surface finish (highest roughness) was achieved via LN_2 cooling at the feed rate of 0.6 mm/rev and axial rotation speeds of 764 rpm , resulting in deep grooves, smearing, and buildup of metal [9]. Cryogenic machining produces the smoothest surface finish (lowest roughness) and an improvement in surface roughness value of 31% as compared to dry machining. The dry machining process yields the roughest surface finish (highest roughness) on increased cutting temperature and plastic deformations [10]. High friction due to lack of lubrication formed the roughest surface under LN_2 cooling, while the smoothest surface under MQL + LN_2 cooling with a TiAlN-coated tool was 18.52% better than LN_2 cooling for surface quality [11]. The roughest surface ($0.35 \mu\text{m}$) produced with non-cryogenic treated PVD insert, the smoothest surface ($0.07 \mu\text{m}$) was produced using cryogenic-treated PVD inserts [12]. The highest surface roughness was produced while machining with uncoated cutting tools at a cutting speed of 20 m/min where surface roughness (R_a) value was more than $0.20 \mu\text{m}$. The lowest surface roughness was obtained while machining with cryogenically treated TiAlSiN/TiSiN/TiAlN-coated tools at a cutting speed of 40 m/min with the R_a values below $0.12 \mu\text{m}$ [13]. The optimal surface finish of $0.21 \mu\text{m}$ was attained at a with cryogenically treated inserts, whereas a roughness of $1.05 \mu\text{m}$ was determined at the least favorable conditions with a cutting speed of 90 m/min and a feed rate of 0.25 mm/rev [14]. The smoothest surface finish (lowest roughness) was generated in Titanium alloy at the cutting speed of 50 m/min and depth of cut of 1 mm . Conversely, high surface roughness was associated with lower cutting speeds ($30\text{--}40 \text{ m/min}$) and shallower depths of cut (0.50 mm and 0.75 mm), yielding undesired surface quality [15]. The smoothest surface finish (lowest roughness) was achieved using DCT-coated tools, reducing roughness by up to 28.5% compared to NCT. The roughest surface finish (highest roughness) was produced by uncoated tools due to higher tool [16]. The best surface finish was obtained with a roughness of $0.72 \mu\text{m}$ at cutting speed of 55 m/min , feed rate of 0.02 mm/rev , and depth of cut of 1 mm . Worst, surface finish values of roughness $1.43 \mu\text{m}$, have been produced with a cutting speed of 35 m/min , feed rate of 0.06 mm/rev , and depth of cut of 0.5 mm [17].

4.3 Effect on cutting forces

Cutting Speed v/s Cutting Force under Different Conditions [4,5,10]

The increasing tool wear went together with an increase in the cutting force. Compared with the CVD insert, the PVD insert designed with wiper geometry behaved much more stably, producing a lower cutting force [1]. Larger cutting speeds and rates of feeding brought forth cutting force increases that led to increased tool wear. However, they had an impact on improved surface finishes thus introducing tool durability against surface quality trade [2]. The cryogenic turning situation endured a cutting force about 7% higher than dry and wet conditions due to the hardening of the work material [3]. All of the speeds show lowest cutting force in CMQL due to proper cooling and lubrication. Cryogenic machining increased the cutting force because it hardened the workpiece, causing more difficult cutting. The forces caused by MQL were less than dry machining but were less effective than CMQL [4]. MQL-CT showed the lowest cutting force due to the joint effect of lubrication and wear reduction of the tool. DRY machining produced the highest cutting force because of no lubrication and the increase of friction. The cutting forces for DRY-CT and MQL were lower than that of DRY but greater than that of MQL-CT [5]. The cutting force was increased dramatically in dry machining, the lowest cutting forces were obtained around the under lubricated conditions [6]. Dry machining gives maximum cutting force due to the absence of coolant, which increased friction during the cutting process, the lowest cutting forces were observed using cryogenic lubrication

(Cryo + MQL), as there was much less heat generated, allowing smoother cutting [7]. Highest cutting force was recorded under CO₂ cooling due to more hardness in the workpiece in lower temperatures. On the other hand, the cutting forces were lower from conventional wet lubrication, resulting in better lubrication in reducing tool resistance [8]. Due to the increased cutting force, higher feed rates and spindle speeds produced more tool wear and surface roughness. Cooling with CO₂ resulted in smoother chips and enhanced surface integrity, while LN₂ cooling produced more strain hardening and increased surface micro-hardness. This emphasizes the importance of optimizing cooling methods and cutting parameters to achieve desired effects in the machining process [9]. The greater cutting forces were observed in dry machining conditions due to the friction and temperature. In cryogenic machining either cutting forces were lowest, reducing the force by 19% as compared to dry conditions [10]. The highest cutting force recorded was 451.51 N, which occurred during LN₂ cooling, the lowest cutting force recorded was 402.9 N, which occurred with MQL + LN₂ cooling, combining cooling and lubrication [11]. Although the cutting force measurement was indirectly imputed, the trends suggest that cryogenic-treated inserts perform better in high speeds and thereby reduce the resistance to cutting [12]. Under low cutting speed conditions (about 20 m/min), uncoated tools recorded a higher cutting force, while at higher cutting speeds of about 40 m/min, cryogenically treated nanocomposite-coated tools created lesser cutting force occurred [13]. Higher cutting speeds (150-180 m/min) led to smoother surfaces and reduced tool wear, lower cutting speeds (90-120 m/min) resulted in higher cutting forces, increased tool wear, and rougher surfaces [14]. The study indicates that with increased speeds, the tool wear is reduced, and the surface finish becomes better, at higher speeds, the machine works more efficiently [15]. DCT-coated tools reduced cutting forces by 23-27% compared to NCT tools and by 25.6-33.8% compared to uncoated tools [16]. Bigger cutting forces were recorded at the low cutting speed of 35m/min and a high feed rate of 0.06 mm/rev, smaller cutting forces were recorded at higher speeds, 55m/min [17].

V. Conclusion

The Review shows that, the application of the techniques of CMQL (Cryogenic Minimum Quantity Lubrication) and cryogenically treated inserts gives a huge edge to the process of machining. This is because CMQL cools and lubricates the tool while reducing wear; cryogenically treated inserts were used to increase tool hardness and wear resistance. Both these techniques together demonstrate longer tool life, smoother surface finish, and lower cutting forces. While CMQL alone can produce excellent results in machining, its combination with cryogenically treated inserts ensures even maximum benefit by lowering friction, heat, and damage to the tool. CMQL with cryogenically treated inserts enhances surface quality and cutting forces as compared to dry machining, which produces increased wear and rougher surfaces. Hence, this becomes the preferred machining procedure especially when it comes to harder materials such as Inconel and Incoloy alloys.

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