Cryogenic Cooling For Aluminum Alloys

Mr. Deepu T[1], Mr. Ajith Mohan M[2], Dr. Shine K[3], Ms. Sivanandhana A[4]
[1] Assistant Professor, Jawaharlal College of Engineering and Technology, Palakkad, Kerala, India
[2] Assistant Professor, Jawaharlal College of Engineering and Technology, Palakkad, Kerala, India
[3]Professor and Head MED, Jawaharlal College of Engineering and Technology, Palakkad, Kerala, India
[4]Final year ME Student, Jawaharlal College of Engineering and Technology, Palakkad, Kerala, India

***Abstract*: The study explores the potential of cryogenic cooling in improving tool wear and surface quality in machining AA2024-T351 alloy. The experiments were conducted under dry, minimal quantity lubrication (MQL), liquid nitrogen (LN2), and carbon dioxide (CO2) conditions. The research aimed to understand the critical tool wear factors and physical phenomena under sustainable cooling environments. The results showed that cryogenic cooling significantly improves tool life and tribological characteristics, enhancing the work piece's precision and surface quality.**

***Index Terms*— Cryogenic, AA2024-T351 alloy, LN2, MQL, CO2, tribology**

I. INTRODUCTION

Aluminum alloys are widely recognized for their lightweight properties, strength, and excellent thermal and electrical conductivity, making them indispensable in various industries such as aerospace, automotive, and electronics. These alloys are also gaining importance in biomedical applications due to their biocompatibility and corrosion resistance. However, despite their numerous advantages, machining aluminum alloys poses significant challenges. The formation of continuous chips, high cutting temperatures, and rapid tool wear often result in poor surface finish and dimensional inaccuracies, which can impact the quality of the final product, especially in precision-driven sectors like aerospace and biomedical fields. The soft and ductile nature of aluminum leads to its tendency to stick to cutting tools, increasing friction and tool wear. Traditionally, cooling and lubrication are achieved through the use of conventional cutting fluids. These fluids help control heat generation and reduce friction, but they also pose significant environmental, health, and disposal challenges due to their chemical composition. To overcome these limitations, there is a growing interest in more sustainable and efficient cooling solutions, such as cryogenic cooling. This innovative technique uses extremely low-temperature gases, such as liquid nitrogen (LN_2) or carbon dioxide (CO_2), to cool the cutting zone during machining. Operating at temperatures below −150°C, cryogenic cooling rapidly absorbs heat, reducing the temperature in the machining area, which results in lower cutting forces, reduced tool wear, and improved surface integrity.

II. IMPORTANCE OF COOLING AND LUBRICATION IN MACHINING ALUMINUM ALLOYS

Cooling and lubrication are crucial in the machining of aluminum alloys, as they mitigate heat generation and reduce friction between the cutting tool and work piece. Aluminum alloys, being soft and ductile, produce high temperatures during machining, leading to rapid tool wear and compromised surface quality.

Effective cooling strategies are essential to dissipate heat generated in the cutting zone, particularly in high-speed machining operations. Excessive heat can degrade the cutting tool and cause thermal expansion in the work piece, leading to dimensional inaccuracies. Cooling ensures the integrity of the machined part and prevents heat-related defects.

Lubrication is vital for reducing friction between the cutting tool and work piece. Lower friction leads to less wear on the tool and a smoother cutting process. Traditional cutting fluids achieve both cooling and lubrication, enhancing tool performance, improving chip evacuation, and maintaining a high-quality surface finish.

However, traditional fluids have environmental concerns, health risks, and high disposal costs due to their chemical content. This highlights the need for more sustainable and effective solutions. Modern industries demand cooling systems that improve machining performance while adhering to stricter environmental regulations.

Cryogenic cooling emerges as a viable alternative, using extremely low-temperature gases like liquid nitrogen (LN_2) or carbon dioxide (CO_2) to control heat in the cutting zone. This method improves tool life and surface quality while providing an environmentally friendly solution, promoting a healthier workplace.

CRYOGENIC COOLING

Cryogenic cooling is an advanced cooling technique that utilizes extremely low temperatures to enhance the machining process. This method has gained popularity in recent years due to its effectiveness in improving tool performance and surface quality when machining challenging materials like aluminum alloys. By employing cryogenic fluids such as liquid nitrogen (LN_2) and carbon dioxide (CO_2), manufacturers can significantly reduce cutting temperatures and improve overall machining efficiency.

TYPES OF CRYOGENIC COOLING

1. *LIQUID NITROGEN (LN2):*
* Temperature: -196°C
* Cooling Effectiveness: LN_2 is one of the most effective coolants due to its extremely low boiling point..
2.*CARBON DIOXIDE (CO_2):*
* Temperature: -78°C
* Cooling Effectiveness: While CO_2 does not achieve the same low temperatures as LN_2, it is still highly effective in reducing heat during machining.

III. COOLING METHODS USED IN MACHINING ALUMINUM ALLOYS

Various cooling methods are employed in the machining of aluminum alloys to enhance performance and address the challenges associated with high cutting temperatures, tool wear, and surface integrity. Each method has its unique advantages and limitations, influencing the overall efficiency of the machining process. Below are the primary cooling methods utilized.

DRY MACHINING

Dry machining is a process that doesn't use cooling or lubricating fluids. While it's simple and cost-effective.

MINIMAL QUALITY LUBRICATION (MQL)

MQL applies a small amount of lubricant directly to the cutting zone, offering: Reduced Tool Wear, Improved Surface Finish, Environmental Benefits However, MQL's cooling efficiency is limited compared to cryogenic methods.

LIQUID NITROGEN (LN_2) COOLING

Liquid nitrogen cooling employs LN_2 as a cryogenic fluid to cool the cutting tool and workpiece during machining. Key benefits include:Effective Heat Absorption: LN_2 has a boiling point of −196°C, providing significant cooling capabilities, reducing tool wear and enhancing machining performance.Improved Tool Life:

CARBON DIOXIDE (CO_2) COOLING

Carbon dioxide cooling uses CO_2, often delivered in a snow or gas form, as a cooling medium. Its characteristics include: Versatile Cooling Performance: CO_2 can achieve temperatures as low as −78°C, providing effective cooling similar to LN_2 and the process is cost-effective and is having less environmental impact

IV. TYPES OF TOOL WEAR IN MACHINING

Tool wear is a significant concern in machining processes, especially when working with aluminum alloys, as the cutting environment can lead to rapid degradation of the cutting tool. Various types of tool wear occur during machining, each impacting the tool's effectiveness and the quality of the machined surface. The cooling method used plays a vital role in reducing tool wear and enhancing the overall performance of the cutting tools. Below are the primary types of tool wear observed in machining.

NOSE WEAR

Nose wear occurs at the rounded tip of the cutting tool, which is referred to as the tool's nose radius. This type of wear impacts the tool's ability to maintain accurate cutting profiles, especially in finishing operations. High cutting temperatures and continuous friction between the tool's nose and the workpiece led to nose wear. Inadequate cooling methods, such as dry machining, exacerbate this problem. Nose wear leads to dimensional inaccuracies, poor surface finishes, and shorter tool life.

FLANK WEAR

Flank wear takes place on the tool's flank face, which is adjacent to the cutting edge. This type of wear is primarily due to the abrasive interaction between the tool and the machined surface. Excessive friction and high temperatures during machining contribute to flank wear. Tools used in dry or inadequately cooled conditions are prone to rapid wear in this region. Flank wear leads to a reduction in the tool's cutting efficiency, increasing the roughness of the machined surface and requiring more frequent tool replacements.

CRATER WEAR

Crater wear develops on the rake face of the cutting tool, where the chips slide off during machining. This wear type forms a depression or crater, affecting the tool's strength and sharpness. High thermal and mechanical stresses at the tool-chip interface are the primary causes of crater wear. Improper cooling, which fails to dissipate heat effectively, accelerates crater formation. Crater wear weakens the cutting tool and leads to poor chip control, higher cutting forces, and eventually tool failure if left unchecked.

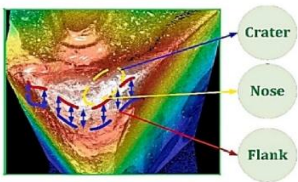

Fig. 1: Types of tool wear.

IMPORTANCE OF MACHINING TOOL WEAR

The type and severity of tool wear depend on several factors, including the material being machined, the cutting conditions, and the cooling method employed. Without effective cooling, such as cryogenic techniques, tool wear can significantly impact machining productivity, tool life, and surface quality. In the following sections, we will explore how different cooling methods, particularly cryogenic cooling, can reduce these types of wear and improve machining performance

V. ANALYSIS OF NOSE WEAR, FLANK WEAR AND SURFACE ROUGHNESS

A. NOSE WEAR ANALYSIS

Nose wear, which occurs at the tool's rounded tip (nose radius), significantly affects the precision of the machining process. It can lead to dimensional inaccuracies and a deterioration in surface quality, making it a critical factor to consider in high-precision machining of aluminum alloys.

a) DRY MACHINING

In dry machining, no external cooling or lubrication is applied. This method results in the highest level of nose wear due to the continuous friction and excessive heat generated at the cutting interface. The absence of cooling causes: High Cutting Temperatures: The lack of heat dissipation leads to a rapid increase in the temperature at the tool's nose, accelerating wear. Severe Tool Degradation: Nose wear in dry machining often results in a significant reduction in tool life, as the tool edges degrade faster without cooling support.

b) MQL COOLING

Minimal Quantity Lubrication involves the application of a small amount of lubricant directly to the cutting area, providing moderate cooling and lubrication. The analysis of nose wear in MQL cooling reveals: Moderate Reduction in Wear and Improved Surface Finish

c) LN_2 COOLING

Liquid nitrogen cooling provides an extremely low-temperature environment, significantly reducing the heat generated during machining. Under LN_2 cooling, the analysis shows:

Substantial Reduction in Nose Wear: The rapid absorption of heat by liquid nitrogen results in lower cutting temperatures, which considerably reduces nose wear.

Extended Tool Life: LN_2 cooling preserves the tool's hardness and sharpness, allowing for longer tool life and enhanced precision during machining.

Superior Surface Quality: The significant reduction in wear also contributes to better surface integrity, making LN_2 cooling highly effective for precision applications.

d) CO_2 COOLING

CO_2 cooling is another cryogenic technique that uses carbon dioxide in its solid (snow) or gas form to cool the cutting zone. The analysis of nose wear under CO_2 cooling shows results comparable to LN_2 cooling.

Improved Tool Life: Similar to LN_2, CO_2 cooling extends tool life by minimizing thermal degradation.
Comparable Surface Finish: The reduction in cutting temperatures leads an improvement in surface quality, making CO_2 cooling a viable alternative to LN_2

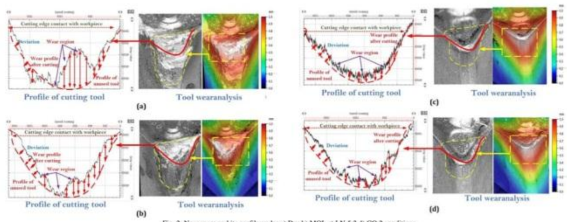

Fig. 2: Nose wear and its profile under a) Dry b) MQL c) LN 5 2 d) CO 2 conditions.

B. FLANK WEAR ANALYSIS

Flank wear, which occurs on the tool's flank face (the area adjacent to the cutting edge), is a critical factor in determining the tool's cutting efficiency and the surface finish of the machined part. Similar to nose wear, flank wear is heavily influenced by the cooling method used during machining. Analyzing flank wear provides insights into the durability of the cutting tool and the effectiveness of the cooling method in reducing tool degradation.

a) DRY MACHINING

Severe Flank Wear: Dry machining experiences the highest level of flank wear among all cooling methods. The continuous high temperatures cause significant abrasion and deformation of the tool's flank face.
Short Tool Life: The rapid wear of the flank face reduces the tool's lifespan, leading to frequent tool changes and increased production costs.
Poor Surface Finish: As flank wear increases, the roughness of the machined surface also worsens, reducing the overall quality of the work piece.

b) MQL COOLING

Moderate Reduction in Flank Wear: MQL reduces the friction between the tool and work piece, leading to a decrease in flank wear compared to dry machining. However, the limited cooling capability of MQL restricts its effectiveness in high-temperature environments. There is an improvement of 15.8% in flank wear while compared to dry machining. Improved Surface Quality:

c) LN_2 COOLING

Significant Reduction in Flank Wear: LN_2 cooling drastically reduces the cutting temperatures, which leads to a substantial decrease in flank wear. The tool's flank face experiences less abrasion and thermal stress, resulting in extended tool life. There is an improvement of 52.6% in flank wear while compared to dry machining.
Enhanced Machining Performance: The significant reduction in flank wear improves the tool's cutting performance, allowing for faster machining speeds and better precision.
Superior Surface Finish: LN_2 cooling ensures a smoother surface finish by reducing the interaction between the tool's worn flank face and the work piece.

d) CO_2 COOLING

Comparable Reduction in Flank Wear: CO_2 cooling reduces flank wear almost as effectively as LN_2 cooling. While CO_2 may not reach the extreme low temperatures of LN_2, it still provides sufficient cooling to minimize wear. There is an improvement of 36.8% in flank wear while compared to dry machining.
Improved Tool Life: Like LN_2, CO_2 cooling helps extend tool life by reducing the thermal and mechanical stresses on the tool.
Comparable Surface Finish: The decrease in flank wear contributes to an improved surface finish, making CO_2 cooling a viable option for high-precision machining.

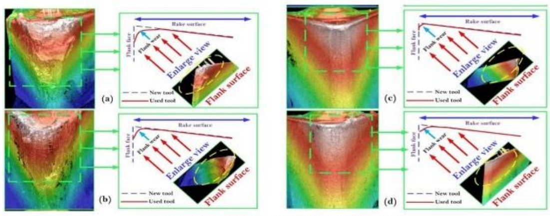

Fig. 3: Flank wear analysis under (a) Dry (b) MQL (c) LN2 and (d) CO2 conditions.

C. *SURFACE ROUGHNESS ANALYSIS*

Surface roughness is a key quality indicator in machining processes, especially when working with materials like aluminum alloys. The cooling method used during machining has a direct impact on the surface finish of the work piece. The ability to control cutting temperatures, reduce friction, and prevent excessive tool wear contributes to a smoother surface with fewer imperfections. Below is an analysis of surface roughness under various cooling methods.

a) DRY MACHINING

Highest Surface Roughness: In dry machining, the absence of cooling and lubrication leads to high cutting temperatures and excessive friction between the cutting tool and the work piece. This results in poor surface quality, with rough, uneven surfaces due to the rapid tool wear and chip adhesion.

Tool Wear Impact: The high rate of tool wear in dry machining directly contributes to surface degradation. As the tool wears down, it loses its sharpness, leading to inconsistent cutting and a lower quality surface finish.

Dimensional Accuracy: The thermal expansion of the tool during dry machining can cause deviations in dimensional accuracy, further affecting the surface quality.

b) MQL COOLING

Moderate Improvement in Surface Finish: MQL cooling introduces a small amount of lubricant to the cutting zone, which helps reduce friction and cutting forces.

Limited Cooling Efficiency: Although MQL reduces friction, its cooling capacity is limited, which can still lead to moderate tool wear

Slight Improvement in Dimensional Accuracy: MQL provides some improvement in dimensional accuracy due to reduced thermal effects on the tool.

c) LN_2 COOLING

Significant Reduction in Surface Roughness: LN_2 cooling provides exceptional cooling efficiency, drastically reducing cutting temperatures and friction.

Improved Surface Integrity: The low temperatures achieved with LN_2 help maintain the sharpness of the cutting tool, leading to a high-quality surface with minimal imperfections.

Excellent Dimensional Precision: The reduction in heat and wear allows for greater dimensional control,

d) CO_2 COOLING

Comparable Surface Finish to LN2: CO_2 cooling provides a cooling effect similar to that of LN_2, with the surface roughness levels being significantly lower than those observed in dry and MQL cooling methods. CO_2 cooling prevents excessive tool wear and maintains tool sharpness, leading to smoother surfaces.

Effective in Improving Surface Quality: Like LN_2, CO_2 cooling enhances surface quality by reducing the interaction between the worn tool and the work piece.

High Precision: CO_2 cooling also enables excellent dimensional accuracy by reducing thermal distortion and minimizing tool degradation during the machining process.

VI. TRIBOLOGICAL EFFECTS

Tribology is the study of friction, wear, and lubrication in surfaces that interact in relative motion. In machining processes, understanding tribological behavior is crucial as it directly impacts tool wear, surface finish, and overall machining efficiency. The cooling method used significantly influences the tribological characteristics, especially when machining aluminum alloys. The Friction and wear behavior between the cutting tool and the work piece are influenced by the temperature at the cutting interface, lubrication conditions, and the material properties. Below is an analysis of the tribological effects observed under different cooling methods.

A.*FRICTIONAL BEHAVIOR IN DIFFERENT MACHINING METHODS*

Dry machining has the highest friction while, MQL cooling has moderate friction reduction due to the use of lubricants. LN2 and CO2 cooling has significant reduction in friction and have lower cutting forces, the also provide high quality surface finish compared to dry machining and MQL cooling.

WEAR REDUCTION

One of the most important tribological aspects of machining is tool wear. Effective cooling reduces wear by minimizing friction and heat generation.

Dry Machining: The high friction in dry machining leads to severe wear, reducing tool life and increasing production costs due to frequent tool replacements.

MQL Cooling: While MQL helps reduce friction and wear to some extent, it is not as effective as cryogenic cooling in minimizing wear during high-speed or high-temperature machining operations.

LN2 and CO2 Cooling: Both LN2 and CO2 significantly reduce wear by maintaining low friction and cutting temperatures, resulting in extended tool life and improved performance. LN2 is typically more effective in extreme conditions, but CO2 offers a comparable solution in many scenarios.

Practical Applications of Cryogenic Cooling

Cryogenic cooling is used in various industries that require high precision, tool longevity, and improved surface quality in machining. Key applications include:

1. Aerospace Industry: Producing components with high precision and minimal defects.
2. Automotive Industry: Machining aluminum alloys for engine components, transmission parts, and structural elements.
3. Biomedical Sector: Manufacturing medical devices and implants with high precision and biocompatibility.
4. Electronics Manufacturing: Producing heat sinks, casings, and other components with precise surface quality and dimensional accuracy.

VII. CONCLUSION

Cryogenic cooling has proven to be a highly effective solution for addressing the challenges of machining aluminum alloys, particularly in terms of managing high temperatures, reducing tool wear, and improving surface integrity. As discussed in this report, the use of cryogenic coolants such as liquid nitrogen (LN_2) and carbon dioxide (CO_2) allows for rapid heat dissipation, leading to enhanced tool life and better surface finishes in comparison to traditional cooling methods.

REFERENCES

[1] M.K. Gupta, P. Niesłony, M.E. Korkmaz, G.M. Królczyk, M. Kuntoğlu, P. Pawlus, M. Jamil, M. Sarıkaya, “Potential use of cryogenic cooling for improving the tribological and tool wear characteristics while machining aluminum alloys”, Tribology International, Volume 183, 2023

[2] Liu, M., Li, C., Zhang, Y. et al. “Cryogenic minimum quantity lubrication machining:from mechanism to application.” Front. Mech. Eng., Volume 16, 2021, pp 649–697.

[3] Divya Zindani, Kaushik Kumar, “A brief review on cryogenics in machining process.”, SN Applied Sciences, Volume 2, Issue 6, 2020