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Review of Cryogenic Cooling in the Machining Process of Ti-6Al-4V Titanium Alloy

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ABSTRACT: Titanium alloy has a wide range of application in various fields of engineering. Titanium alloys, particularly Ti-6Al-4V, are extensively used in aerospace, automotive, and biomedical industries due to their exceptional mechanical properties. However, the machining of these alloys presents significant challenges, including poor machinability, high tool wear, and surface integrity issues. Cryogenic cooling has emerged as a promising technique to address these challenges by enhancing tool life, improving surface finish, and reducing residual stresses. This paper provides a comprehensive review of the application of cryogenic cooling in the machining of Ti-6Al-4V titanium alloy. It discusses the fundamentals of cryogenic cooling, its effects on tool wear mechanisms, surface integrity, and machining performance. Furthermore, recent advancements, challenges, and future directions in the utilization of cryogenic cooling for Ti-6Al-4V machining are critically examined. The review underscores the potential of cryogenic cooling as a viable solution to enhance the efficiency and effectiveness of machining processes for titanium alloys, thus contributing to the advancement of manufacturing technology in various industrial sectors.

KEYWORDS: Cryogenic cooling, Ti-6Al-4V, Surface integrity, Tool wear mechanism.

I. INTRODUCTION

The bulk of energy utilized during machining operations is typically transformed into heat. A significant portion of issues arising in machining stem from the heat generated and the resulting elevated temperatures. Hence, meticulous consideration in selecting the appropriate cutting fluid is crucial. This selection can substantially impact various factors such as tool longevity, cutting forces, power usage, machining precision, surface quality, and more. It is crucial to utilize cutting fluids to minimize friction and dissipate heat promptly during machining processes. Various machining environments include:

1. Dry machining.
2. Flood/Wet cooling.
3. Minimal Quantities Lubricant (MQL)
4. High-pressure cooling
5. Chilled air cooling

1. Dry Machining: Opting for dry cutting, which involves metal cutting without coolant, presents numerous advantages for sustainable machining practices. This method not only prevents pollution, reduces cleaning and disposal costs by eliminating swarf residue, but also mitigates health hazards such as skin injuries and allergies. Embracing dry machining aligns with sustainability objectives, offering a safer, cleaner, and economically viable solution for metal cutting processes.

2. Flood/wet Cooling: Employing cutting fluids for lubrication, cooling, and chip removal during machining enhances various aspects of the process. By generously applying soluble oil in the cutting area, these fluids prolong tool lifespan, refine surface quality, improve precision, reduce cutting force, and minimize vibrations. In essence, cutting fluids play a pivotal role in streamlining machining operations, ensuring prolonged tool durability, enhanced product aesthetics, precise measurements, and smoother machining processes.

3. Minimal Quantities Lubricant (MQL): Minimum Quantity Lubrication (MQL) involves utilizing a combination of compressed air and oil droplets at the chip-tool junction, surpassing traditional flood coolant and dry machining methods. MQL minimizes waste, decreases environmental impact, and efficiently lubricates the cutting process, leading to extended tool longevity and superior surface finishes.

4. High Pressure Cooling: Implementing high-pressure cooling entails directing a forceful stream of water-soluble oil to cool the cutting zone during machining. This technique enhances machining efficiency by effectively dissipating heat, preventing tool wear, and refining surface finish. The precise delivery of high-pressure cooling ensures optimal performance and extends the tool's lifespan.

5. Chilled Air Cooling: Utilizing chilled air cooling involves circulating cold air to dissipate heat efficiently. By employing a system that lowers air temperature before directing it to cool electronic components or industrial machinery, chilled air cooling provides an effective method for maintaining optimal operating temperatures and preventing overheating.

II. LITERATURE REVIEW

2.1 Literature Review of Turning Process

Most research efforts are directed towards cryogenic machining in turning operations due to its relative ease of comprehension. Turning, as a machining process, involves the utilization of a single point cutting tool to eliminate material from the surface of a cylindrical workpiece undergoing rotation. This tool is linearly fed in a direction that is both parallel and aligned with the axis of the workpiece's rotation. This machining technique provides a clear and straightforward platform for studying the effects and benefits of employing cryogenic cooling methods.

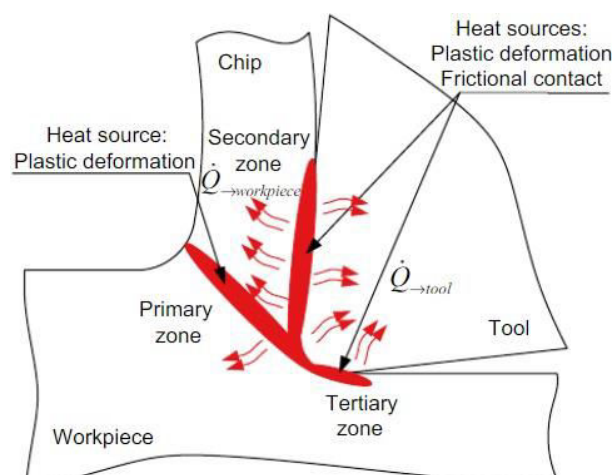


Figure no.1: - Cutting zone in turning process.

Yields and Muammer Nalbant et al. (2008) [1] highlighted that cryogenic cooling stands out as one of the most advantageous methods in metal cutting operations, leading to notable enhancements in tool life, surface finish, and reduction in tool wear. Ahsan Ali Khan and Mirghani (2008) corroborated these findings, reporting up to a fourfold increase in the tool life of cutting inserts through the utilization of cryogenic cooling. Their study utilized modified cutting inserts supplied with liquid nitrogen.

M. Dhananchezian and M. Pradeepkumar et al. (2009) [2], it was found that cryogenic cooling significantly impacts cutting temperature, cutting force, chip thickness, and shear angle in AISI 1045 Steel and Aluminium 6061-T6 alloy machining. Results indicated a temperature reduction of 19-28% and a maximum 15% increase in cutting force compared to dry machining for AISI 1045 Steel. Similarly, machining Aluminium 6061-T6 alloy saw temperature reductions of 27-39% and a maximum 10% increase in cutting force.

Dilip Jerold and Pradeep Kumar et al. (2011) [3], various parameters including cutting temperature, chip thickness, surface roughness, and cutting forces were investigated. The study utilized AISI 1045 Steel as the work material and employed a multicoated carbide cutting tool. The findings revealed that liquid nitrogen (LN₂) emerged as the optimal alternative cutting fluid, demonstrating reduced cutting temperature, minimized cutting forces, and enhanced surface finish compared to other fluids tested. LN₂ proved to be particularly effective in improving machining performance, showcasing its potential as a superior choice for achieving efficient and high-quality machining outcomes.

In a study conducted by **Sunil Magadum et al.** in 2014 [4], experiments were conducted on a lathe using coated carbide tools with both cryogenic and flood coolants. The experiments were conducted at cutting speeds of 200 and 250 meters per minute, with a constant feed rate depth of cut of 0.2mm per revolution and 1.5mm respectively. Various

parameters such as tool wear, tool life, and cutting forces were measured. The results revealed that cryogenic machining demonstrated improved tool life compared to conventional flood machining.

Zhao et al. (2016) [5] showcased cryogenic machining's efficacy in prolonging tool lifespan by mitigating tool wear and bolstering resistance against thermal degradation. Through reduced cutting temperatures and enhanced lubrication at the tool-chip interface, cryogenic cooling effectively preserves tool integrity, promising significant improvements in machining durability and performance.

Tze Chuen Yap et al. (2019) [6] confirmed Cryogenic turning benefits superalloys, ferrous metals, and polymers uniquely. Their study emphasized industry challenges in adopting cryogenic machining.

Mark Broomer et al. [7] assessed the cost-effectiveness of cryogenic machining, factoring in extended tool life, increased productivity, and operational costs. Their study underscores the economic viability of implementing cryogenic techniques in machining processes, highlighting potential savings and improved efficiency. Such considerations are crucial for industry decision-makers evaluating the adoption of cryogenic machining technologies, as they weigh the benefits against initial investment and ongoing expenses.

2.2 Literature Review of Milling Process

Milling involves the utilization of rotating cutters to eliminate material from the surface of a workpiece. The milling cutter, acting as a cutting instrument, possesses numerous cutting edges positioned along the axis of rotation.

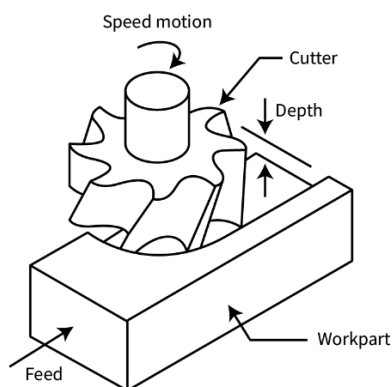


Figure no.2: - Facing milling.

Li et al. (2017) [8] investigated the effects of cryogenic cooling on tool wear and surface integrity during milling of hardened steel. Results indicated a notable reduction in tool wear and improved surface finish compared to conventional methods.

Zhang et al. (2018) [9] focused on the influence of cryogenic cooling on chip morphology and tool life in titanium alloy milling. Cryogenic conditions were found to promote the formation of segmented chips, reducing tool wear and prolonging tool life.

Muhammad Jamil et al. (2019) [10] examined the environmental and economic aspects of cryogenic machining. Despite its benefits in tool life and surface quality, concerns were raised regarding energy consumption and the cost-effectiveness of cryogenic systems.

Gupta et al. (2020) [11] highlighted exploration of advancements in both tool material and geometry. Their study underscored the promising prospects of cryogenic machining in reducing tool wear by leveraging optimized tool designs and materials.

III. CRYOGENIC COOLENTS AND CRYOGENIC MACHINING

In the 1950s, researchers began exploring the application of cryogenic coolants in machining processes. Cryogenic cooling, utilizing extremely low temperatures, revolutionized the removal of heat generated during cutting operations across various materials. Cryogenics, derived from the Greek words 'cryos' meaning ice cold and 'genes' meaning born, pertains to temperatures nearing absolute zero, typically below -153°C .

A myriad of cryogenic coolants, including helium, hydrogen, neon, nitrogen, oxygen, argon, krypton, xenon, methane, ethane, propane, and carbon dioxide, have been utilized. However, liquid nitrogen (LN_2) and carbon dioxide (CO_2) have emerged as prominent choices for machining applications.

Cryogenics, a field focusing on ultra-low temperatures often below -150°C , plays a pivotal role in optimizing machining operations. Cryogenic machining utilizes frigid liquids to cool the machining tool and workpiece, mitigating the adverse effects of heat generation during the process. Extensive research underscores that heat-related issues are primary concerns in machining. Cryogenic fluids combat this problem by rapidly and efficiently dissipating heat, presenting a holistic remedy.

Cryogenic machining represents an innovative material removal technique wherein conventional cutting fluids are substituted with cryogenic mediums such as liquid nitrogen and CO_2 . These liquefied gases are directed into the cutting zone, rapidly cooling the tool and/or workpiece. As the cryogenic medium absorbs heat from the cutting zone, it evaporates into the atmosphere, facilitating efficient heat dissipation and enhancing machining performance.

IV. EXPERIMENTAL SETUP

4.1 Setup of Cryogenic machining using LN_2

The process described refers to the setup of cryogenic machining using liquid nitrogen. Cryogenic machining is a technique used to enhance machining processes by utilizing extremely cold temperatures to improve cutting performance, increase tool life, and reduce heat-induced deformation of workpieces.

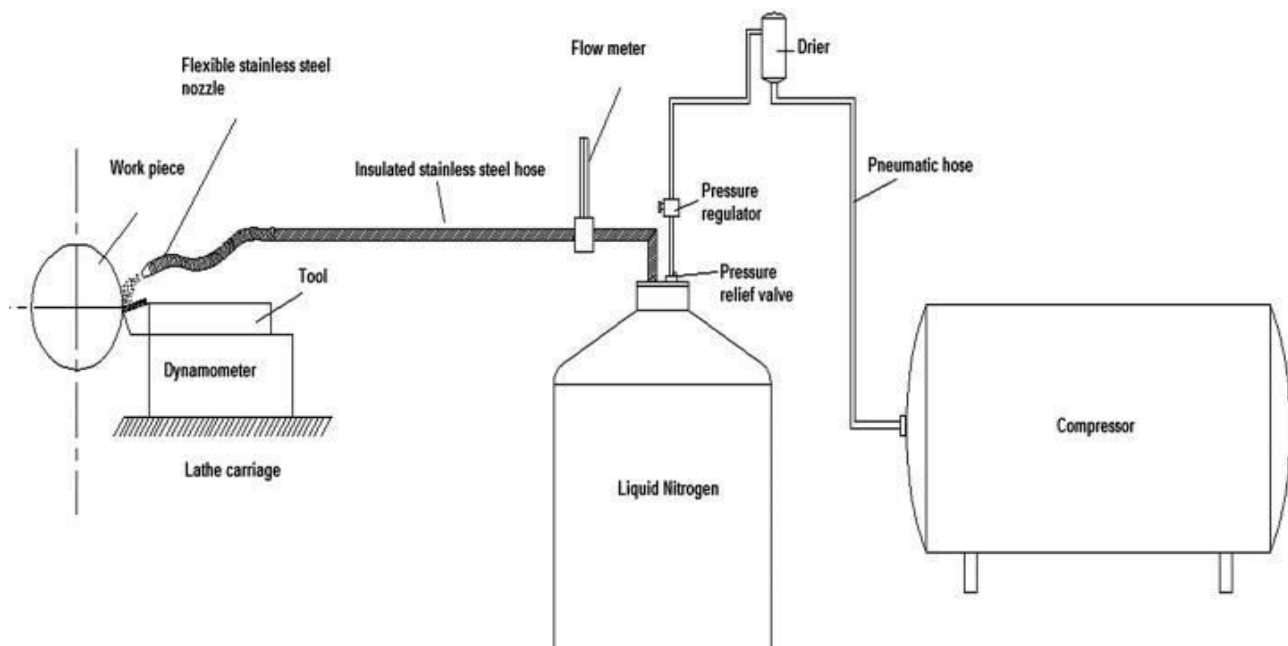


Figure no.3: - Cryogenic cooling setup- LN_2

Here's an explanation of the setup:

1. Cryogenic Liquid Storage Tanks: Cryogenic liquids, such as liquid nitrogen, are stored in specially designed tanks. These tanks can be cylindrical or spherical in shape. They are heavily insulated to maintain the extremely low temperatures of the cryogenic liquid.

2. Pressure Control: Within the storage tanks, pressure control mechanisms are installed to regulate the pressure of the cryogenic liquid. This ensures that the liquid nitrogen remains in a stable state and can be delivered effectively to the machining process. As the liquid nitrogen is sprayed onto the cutting zone, the pressure within the tank itself helps to force the coolant (liquid nitrogen) to the cutting zone. This pressure assists in maintaining a steady flow of coolant to the machining area, ensuring efficient cooling and lubrication of the cutting tool.

3. Spraying Process: In the cryogenic machining setup, the liquid nitrogen is sprayed onto the cutting zone of the workpiece. This spraying process is typically achieved using specialized nozzles or delivery systems. The extreme cold of the liquid nitrogen serves to cool down both the cutting tool and the workpiece rapidly during the machining operation.

Overall, the setup described allows for the effective utilization of cryogenic cooling during machining operations. By storing liquid nitrogen in insulated tanks, controlling its pressure, and using a spraying process to deliver the coolant to

the cutting zone, it can benefit from improved machining performance, increased tool life, and better surface finish on the machined parts.

4.1 Setup of Cryogenic machining using CO₂

The passage describes the setup for cryogenic machining using liquid carbon dioxide (CO₂) as a coolant.

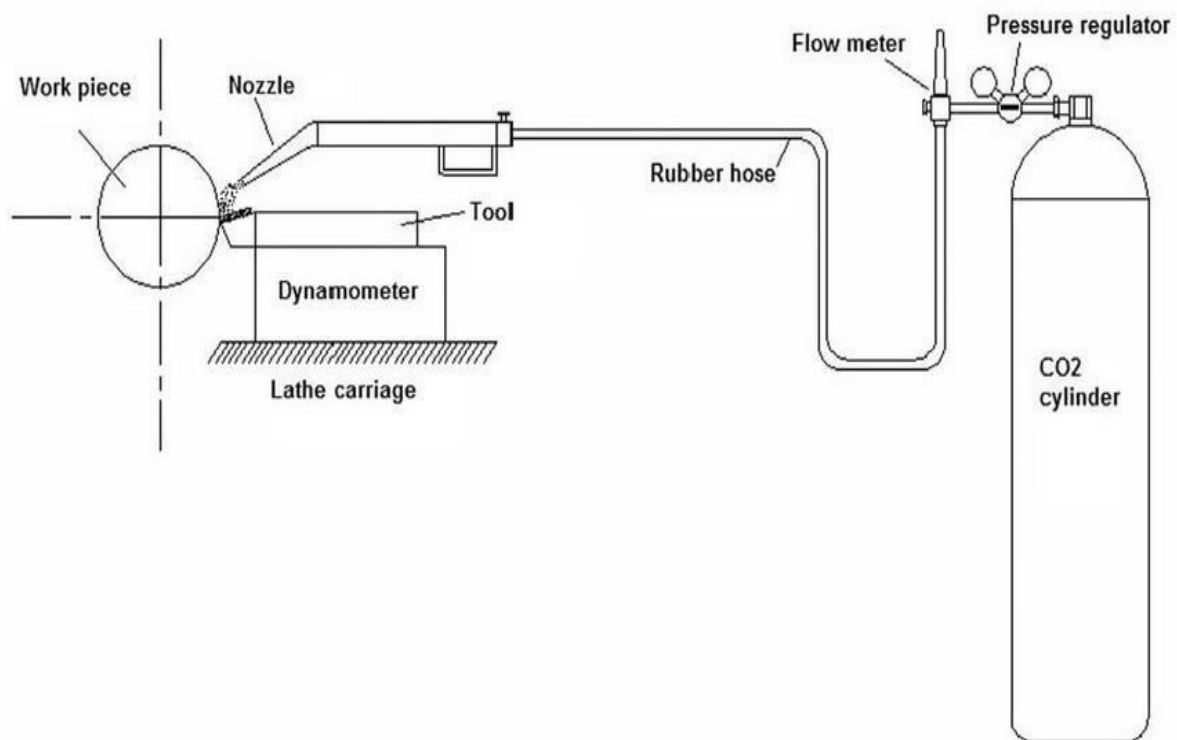


Figure no.4: - Cryogenic cooling setup-CO₂

Here's a breakdown of the setup:

1. CO₂ Cylinder with Pressure Regulator: The process begins with a CO₂ cylinder attached to a pressure regulator. This regulator has two dial indicators:

- a) One indicator shows the pressure inside the CO₂ cylinder.
- b) The other indicator shows the supply pressure, which is likely the pressure at which the CO₂ is being supplied to the machining process.

2. CO₂ Flow Meter: Connected next to the pressure regulator, a carbon dioxide flow meter is used to measure the rate of CO₂ flow. This is crucial for controlling the amount of coolant being supplied during the machining operation.

3. Rubber Hose: One end of a rubber hose is connected to the outlet of the flow meter. Rubber hoses are often used in cryogenic applications due to their ability to withstand low temperatures.

4. Torch: The other end of the rubber hose is connected to a torch. The torch is the delivery mechanism for the CO₂ coolant. It consists of:

- a) **Nozzle Tip:** The torch has a nozzle tip that can be changed as needed. This allows for adjustments based on the specific machining requirements.
- b) **Valve:** The torch also has a valve for controlling the flow of CO₂. This valve can be adjusted to regulate the coolant flow rate or to completely stop the flow when the machining process is not active.

In summary, this setup allows for precise control and delivery of liquid carbon dioxide coolant during cryogenic machining operations, enhancing cooling efficiency and improving machining performance.

V. CONCLUSION

The review of this paper suggests that employing cryogenic cooling presents a distinct approach with numerous advantages in machining, including:

1. Cryogenic cooling offers an environmentally friendly solution by utilizing liquid gas, which evaporates into the atmosphere.
2. Among various cooling methods, cryogenic coolant demonstrates the most significant impact on enhancing tool longevity and refining surface finish.
3. Implementing cryogenic machining, particularly with CO₂ as the cutting fluid, results in decreased cutting forces and improved chip breakability, along with the reduction of chip thickness.

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