iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 Issue: XII Month of publication: December 2019

DOI: http://doi.org/10.22214/ijraset.2019.12077

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.177
Volume 7 Issue XII, Dec 2019- Available at www.ijraset.com

Cryogenic Machining: A Sustainable Solution

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Abstract: ***In the modern manufacturing process metalworking fluid is an essential part of the cutting process. The application of coolant in between the tool and workpiece reduces the friction and carried out heat generated during the process. These cutting fluids are not only harmful to the workers and the environment but also increases the total cost of manufacturing. The cost associated with coolant handling and disposal is nearly 7% to 17% of the manufacturing cost. It is already proven that coolant is the main source of pollution in the manufacturing industries. But, Coolant plays an important role in lubrication, reducing friction and heat dissipation between the workpiece and the tool. Over the years, coolants are found a non-sustainable source in the manufacturing process. In the cryogenic machining process, the cryogenic liquid evaporates and becomes a part of the atmosphere which leaves zero residues. This characteristic makes cryogenic machining a sustainable solution for the industry. Thus, cryogenic machining can be an environmentally friendly alternative to the coolant. This paper is a review of cryogenic machining which will help in understanding the concept and mechanism of cooling in the cutting process.***
Keywords: Cryogenic Machining, Liquid nitrogen, Liquid CO_2, cryogenic cooling, eco-friendly

I. INTRODUCTION

The word cryogenic signifies that any activity below the temperature of – 153 ° C or below. The cryogenic word derives by two words, 'Cryos' means ice-cold and 'genes' means born. When we refer cryogenic liquids we generally focus on liquid nitrogen, oxygen, helium, methane, carbon dioxide, ethane and argon. Our main area of study is on liquid nitrogen and carbon dioxide. The heat generated during all cutting operations can be effectively removed by cryogenic cooling. Cryogenic machining is the metal cutting operation in which conventional coolants can be replaced by cryogenic liquids such as LN_2 (Liquid Nitrogen) and CO_2. These cryogenic liquids are supplied directly to the metal cutting zone and it can cools tool and work. After getting into contact with the Work and tool the heat gets absorbed and cryogenic liquid evaporates in the atmosphere.

There are a variety of methods to convert raw material into finished goods. Machining operations like turning, milling and drilling are well known. Competitive markets demand to force manufacturing industries to constantly increase productivity and taking sustainability measures.

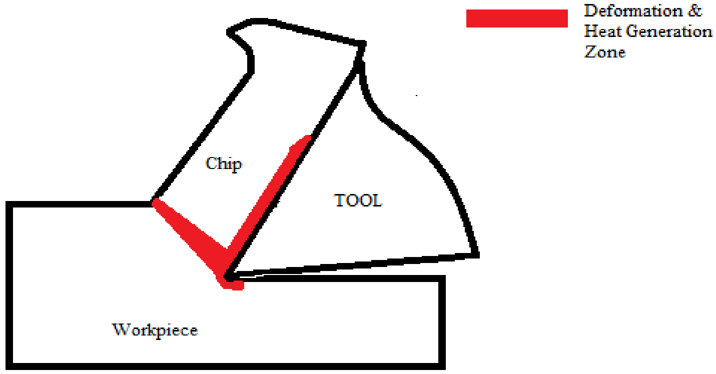

Fig. 1 Deformation and Heat generation zone Between Tool-Work piece interface

Fig.1 shows the deformation and heat generation zone between tool and workpiece during the machining operation. Coolant is supplied in this highlighted cutting zone. The main function of these coolants is to provide cooling, lubrication and reducing friction. These coolants are of two types, one is a water-based solution or water emulsions and the second is lubricants which are oil-based. The major concern with the coolant application is they are hazardous to the workers' health and environment. The chemicals into coolants can cause water pollution and soil contamination. These chemicals can be found in oil-based coolants which are hydrocarbons, phosphorous, sulfur, chlorine and biocides.

II. THE EARLY LIFE OF CRYOGENIC MACHINING

The main challenge in front of scientists and engineers to attain low temperatures to reach up to the liquid state of cryogenic liquids such as oxygen, nitrogen, hydrogen and carbon dioxide. Cryogenic cooling first introduced in 1953 using CO_2 as cryogenic liquid [1]. During machining titanium alloys this liquid CO_2 as coolant can increase the life of carbide tools [2]. Also, the material removal rate while machining titanium increases with the application of LN_2 and CO_2 as coolant [3].

III. CRYOGENIC COOLING MECHANISM

Mechanisms of causing low temperatures of LN_2 and CO_2 are discussed below.

A. *Mechanism of Liquid Nitrogen cooling (LN_2):*

The triple point of nitrogen exists at the pressure of 0.13 bar and temperature of -210 °C. We can find nitrogen in solid, liquid and gaseous state at this stage. At very low temperatures the liquid nitrogen stored in the isolated tanks at very high pressure. When this high pressurized liquid nitrogen supplied to the metal cutting zone at atmospheric temperature then its pressure drops to 1.01325 bar and at -196 °C liquid nitrogen starts boiling [4]. This supplied liquid nitrogen to the cutting zone starts absorbing the heat generated during the metal cutting operation and liquid nitrogen starts evaporating into nitrogen gas and becomes part of atmospheric air. Here, this LN_2 becomes part of 79% of nitrogen gas in the air, this cryogenic liquid is considered as safe and non- combustible chemical [5][6]. Also, after evaporation it leaves no residue in the cutting zone and in an environment, makes LN_2 harmless.

B. *Mechanism of Liquid Carbon Dioxide cooling (CO_2):*

CO_2 only exists at the solid or gaseous state from pressure 0 to 5.2 bar and temperature from -273 °C to -56.6 °C. For liquid CO_2, pressure above 5.2 bar needs to be maintained and this liquid CO_2 is stored in a medium pressure tank at a pressure of 57 bar at 20 °C in liquid form. Pressure-resistant pipes are used to supply liquid nitrogen from medium pressure tank to metal cutting zone. Pressure resistant pipes are used to ensure the same chemical phase during supply. When this liquid nitrogen enters the metal cutting zone, the major drop in pressure is observed. Which causes liquid CO_2 to expand and cool down due to the Joule Thomson effect [7]. When this liquid CO_2 cools down to -78.5 °C, it absorbs heat from the surrounding metal cutting zone and transforms in 60% gas and 40% snow. Dry CO_2, after played its role as coolant, evaporates into the air and leaves no harmful residues, which makes this cryogenic liquid harmless.

IV. CRYOGENIC COOLING PROCESS

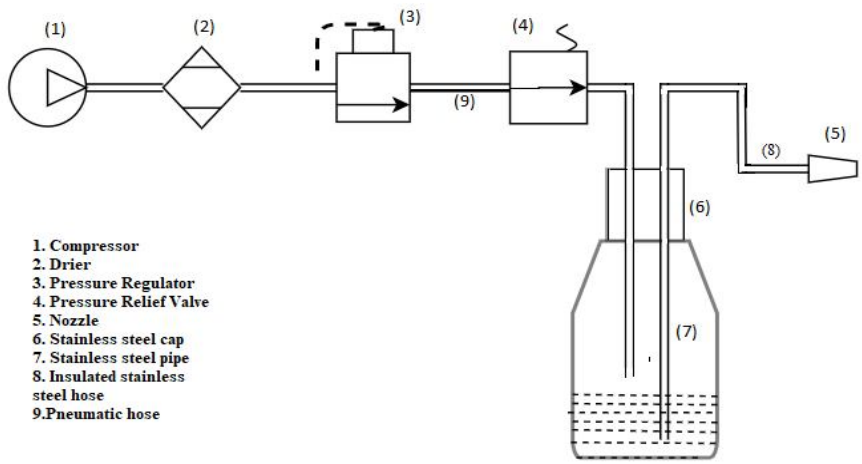

Fig. 2 Cryogenic Cooling setup [8]

The process of cooling the tool and workpiece during the metal cutting operation is known as cryogenic machining. In this process, liquid nitrogen and liquid CO_2 supplied through the storage tank to metal cutting zone instead of water-based & oil-based coolants. Spherical and cylindrical shape storage tanks are used to store high pressurized LN_2 and CO_2. The pressure inside the storage tank is the driving force for the cryogenic liquid to enter the metal cutting zone. Therefore, there is no need for additional energy and efforts required.

The mechanism of supply for cryogenic machining to the cutting zone is also an important parameter in terms of cooling effect. The main difference between two mechanisms i.e. external cooling & internal cooling is discussed below.

TABLE 1
Difference between External and Internal Cooling

External Cooling	Internal Cooling
In this method, the cryogenic liquid supplied through the nozzle. The nozzle is positioned in such a way that cooling liquid enters the aimed cutting zone.	The liquid nitrogen or any other cryogenic liquid supplied through the specially designed tool where these cryogenic liquids enter the metal cutting zone in the nearest proximity to the tool-chip interface.

The highest efficiency of cryogenic liquid cooling can be achieved by delivering the cryogenic liquid to the metal cutting zone into the higher temperature zone. Also, aiming the nozzle as close as possible to the tool-workpiece interface can be beneficial. Sometimes, extremely low temperatures of cryogenic cooling are harmful to the material, because these liquids can change the microstructure and mechanical characteristics of the material.

V. APPLICATION OF CRYOGENIC LIQUID COOLING

A. Materials

Cryogenic machining often referred to difficult-to-machine materials. The materials which are known for high strength characteristics such as aerospace materials and superalloys. Toughness, resistant to corrosion and capable of sustaining strength in extreme conditions such as high temperatures is the characteristics of aerospace materials which makes them abide by the strict safety regulations. The highest possible fuel consumption is controlled by a high strength to weight ratio [9]. These characteristics and the nature of aerospace materials make them very hard for metal cutting operations. Since chips carry out only one part of heat there are chances of high thermal tool load due to low heat conductivity of the aerospace materials. During the metal cutting operation, the friction between the tool and the workpiece leads to the heat generation between tool-chip interfaces which causes 20%-30% of extra thermal energy to be added on the cutting tool. This increases the chances of ductility and acts as a catalyst for tool wear. Adhesion-dissolution-diffusion of the tool material into the running chip at the tool-chip interface and chemical reaction between the tool and chip also causes the tool to wear [10][11]. Research and experiments of cryogenic machining on materials like alloys of steel, nickel, and titanium known as aerospace materials shown good results. Tungsten carbide, low alloy steel AISI 4340, stainless steel and carbon steel shows positive results on cryogenic machining.

B. Tools

Carbide tools with PVD and PCD coatings are commonly used in cryogenic cooling machining. Experiments have been done with Carbon boron nitride (CBN), diamond and ceramic tools. On the basis of a workpiece material tool is selected for the metal cutting. The selection of cutting tools is the most important parameter in the machining. Cutting inserts are exercised in the metal cutting.

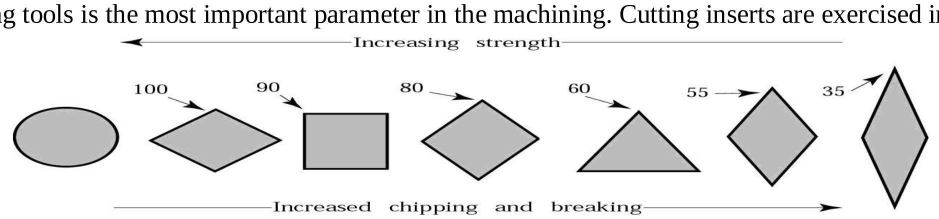

Fig. 3 Shapes of cutting inserts [12]

The properties of the inserts are lower friction between tool-chip interface, higher adhesion, higher resistance to wear and cracking, acting a diffusion barrier, higher hot hardness and impact resistance [12].

VI. ADVANTAGES OF CRYOGENIC MACHINING

Cryogenic machining is environmentally friendly as after evaporation liquid nitrogen and liquid CO_2 become part of the air, which are not harmful. Productivity and tool life increase. This is a cleaner and safer method instead of using the conventional method of cooling. Higher cutting speeds can be achieved with cryogenic machining without increasing the tool wear. Lower risks of health hazards to the worker in contact with the cutting zone. The requirement of traditional mechanical utility systems such as pumps, filters for the handling of coolants has been eliminated which results in fewer energy consumptions.

VII. DISADVANTAGES OF CRYOGENIC MACHINING

The main disadvantage of cryogenic machining is the maintenance of a high pressurized storage tank. The storage and handling of the high pressurized cryogenic liquid can be dangerous and it can cause an explosion in the extreme case. The liquid nitrogen and other cryogenic liquids are costly in nature to consume than conventional coolants. There are chances of low-temperature hazards.

VIII. CONCLUSION

The fundamental mechanism and study have been reviewed on cryogenic machining. From his review, we can conclude that cryogenic machining is eco-friendly since the cryogenic liquid after it's served its purpose evaporates into the atmosphere. This makes cryogenic machining a sustainable solution. Cutting forces can be reduced with the help of liquid CO_2 [12]. The quality of the work surface and the working environment can be improved. The negative impact of an increased in cutting forces can be eliminated using cryogenic cooling.

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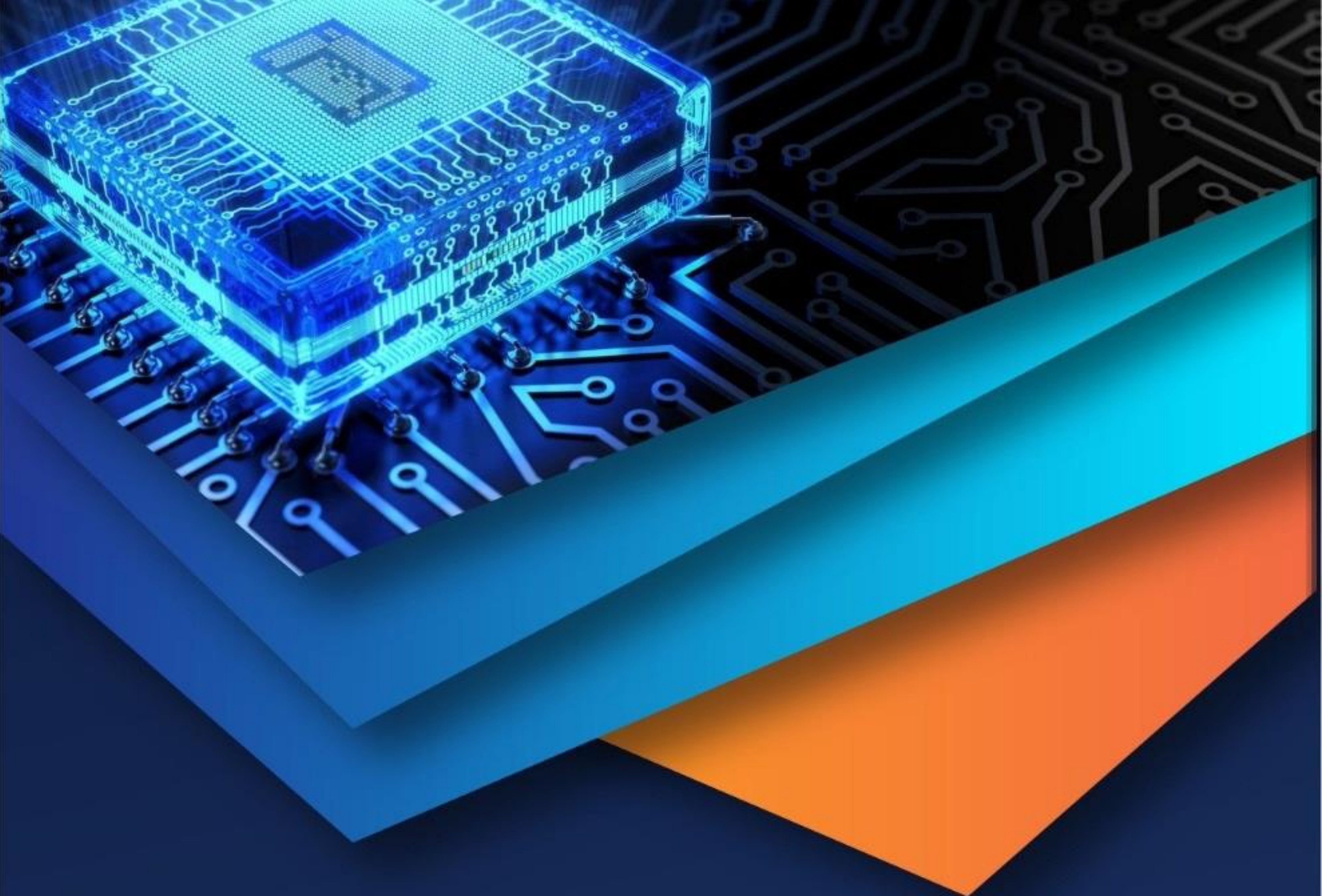

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