# Investigation into applications of cryogenic cooling in machining environment

Anil B Ghubade[1], Anil Kumar[2]
[1, 2,] Assistant Professor, School of Mechanical Engineering, Lovely Professional University, Punjab-144411, India.

## Abstract
Metal cutting industries constantly making effort to increase the production rate at minimum cost. The various challenges are being faced by metal cutting industries such as disposal of cutting fluid, improvement in surface integrity of the components, high quality surface finish etc. The various methodologies are being adapted by researchers to improve machining performance. Cryogenic cooling is one of the methods to improve the production yield at minimum cost with improved quality in the final product. Therefore, the aim of this paper is to investigate the role of cryogenic cooling in machining environment along with its capability and challenges.
**Keywords:** cryogenic machining, Liquid nitrogen, cryogenic turning

## 1. Introduction

Cryogenics in the context of scientific study is referring to material and their behaviour at temperature below -150 degree or even below [1].Cryogenics is the derived from two Greek word, “cryos” means “cold” and “Genic” means “born”. According to US National Institute of Standards and Technology (NIST), cryogenics includes temperature below-180 degree Celsius. Below this temperature the existing gases such as oxygen, nitrogen, hydrogen, neon, helium etc are in liquid state. Owing to desirable characteristics of cryogenic liquid as vapours and gases release from them are extremely cold, they even condense the atmospheric air and forms liquid –air mixture (mist) are most suitable for machining environment. The cryogenic machining was first reported by Bartley in around 1953 who used the liquid $CO_2$ as coolant [2]. Cryogenic cooling is innovative and sustainable methodology which is capable of replacing the existing cooling techniques such as oil based cutting fluids, flooded cooling etc which has detrimental effect on environment and possess challenges to dispose it [3]. Various sustainable machining approaches have been reported in the literature such as dry machining [4], minimum quantity lubrication (MQL)[5],application of tool coating[6], modification of surface texture of tool[7] etc. researchers employing these techniques to improve the machining performance because the requirement of machining products in aerospace, automobile, biomedical applications is growing at a faster rate. Also, most of the materials used in machining have higher strength, strong resistance to deformation and therefore, to machine these materials with desired surface integrity poses great challenge. So to achieve desired quality in the final product, metal cutting industries has to improve the existing technologies and adapt the recent technology such as use of high quality tool, coating technology over the tool and innovative cooling methodologies such as cryogenics. Although the liquid carbon dioxide (LCO2) is not recommended for machining applications as this liquid $CO_2$ when comes out and forms gaseous form is heavier than atmospheric oxygen and cause breathing problem to the operator. In this paper, the role of cryogenics in machining environment in context to various materials and machining processes and its effect to improve the machining performance has been investigated.

**2. Heat generation in metal cutting**

The process of metal cutting involves generation of high temperature in tool as well as in workpiece. Therefore, the thermal aspects of elements of metal cutting are very much important which significantly affect the performance of machining process. The heat is generated in metal cutting zone is results of primary deformation along the shear plane(primary deformation zone), interaction of chip and rake face of the tool(Secondary deformation zone) and interaction of flank face and already machine surface of the tool(Tertiary deformation zone). The region of heat generated as shown in Fig 1 and represented by $Q_1$, Q2 and $Q_3$[8].

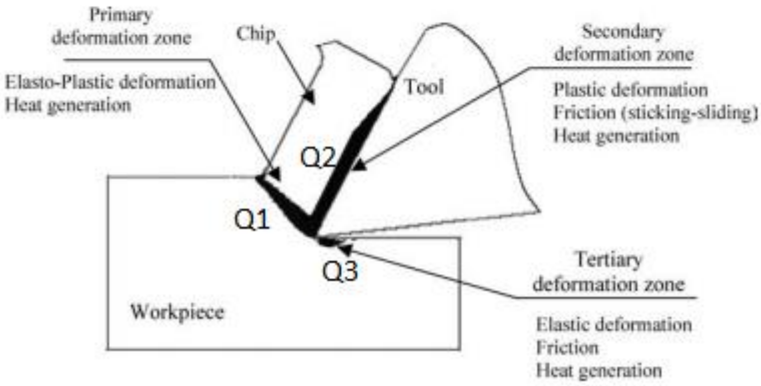


**Fig 1:** Sources of heat generation [$Q_1$, Q2 and $Q_3$] in the orthogonal cutting process.

The amount of heat generated in primary and secondary deformation zone is highly depends upon cutting condition whereas the temperature generated tertiary zone is highly depends on flank and already machined surface. The most of the heat generated in machining zone is carried away by three elements namely chip, cutting tool and workpiece. Chip carried away around 60-80% of the heat, workpiece carries heat around 10-15% followed by cutting tool. Therefore, the application and location of cryogenic treatment over the machining elements is crucial to reduce the temperature of machining zone to the permissible limit to avoid failure of the tool in the form of plastic deformation, thermal cracking etc, as well as to avoid distortion and warpage in the job.

## 3. Cryogenic machining

### 3.1 General set up for liquid nitrogen (LNO2) cryogenic machining

The set up for liquid nitrogen (LNO2) is shown in Fig 2.The liquid nitrogen cryogenic set up comprises of container for liquid nitrogen, Air compressor, drier, flow meter pneumatic hose piping, and nozzle and safety devices.

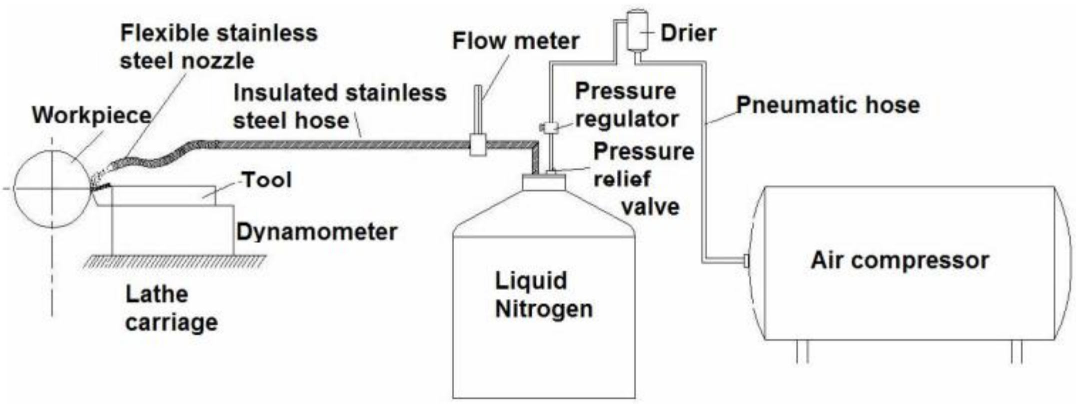


**Fig 2:** Experimental set up of liquid nitrogen (LNO2) cryogenic machining

The working of LNO2 cryogenic machining, supplies the compressed air from the compressor into the liquid nitrogen container through the air dried so that any moisture present in the air can be removed before it enters into the container. Pressure relief valve and pressure regulator ensure the required pressure in the contained to 2 bar. The liquid nitrogen form the container is supplied to machining zone via insulated stainless steel hose pipe. This insulation to the hose pipe ensures the temperature of liquid nitrogen should not fall, when it is getting transferred through the hose.

### 3.2 **General set up for liquid carbon dioxide (LCO2) cryogenic machining**

The set up of liquid carbon dioxide (LCO2) is shown in Fig 3. It comprises of Liquified carbon dioxide cylinder, Flow meter, hose pipe, nozzle etc. the liquid CO2 is stored in cylinder having capacity around 32 liter.Two pressure regulators are used with CO2 container, one shows the Liquified CO2 pressure inside the cylinder whereas the second pressure regulator indicate the supply LCO2 pressure.

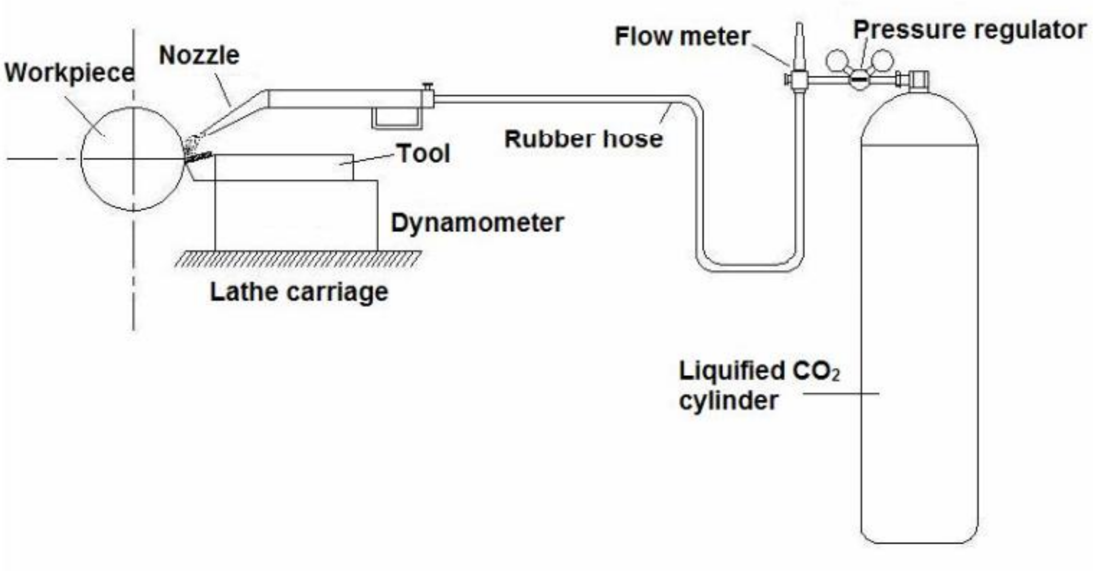


**Fig 3:** Experimental set up of liquid carbon dioxide (LCO2) cryogenic machining

Next to the supply regulator, a flow meter is attached which measure the amount of liquid CO2 coolant.Finally,the measure amount of Liquid CO2 is supplied to machining zone through rubber hose pipe.

**4. Application of cryogenics in machining environment**

Wang, Z. Y et al.[9] Investigated the machining of advanced ceramics with liquid Nitrogen cooled polycrystalline cubic boron nitride (PCBN) tool, tantalum, Inconel alloy and titanium alloy with cemented carbide tool. The result shows that with liquid nitrogen the temperature in machining zone reduced to lower value and hot hardness of tool remains intact. Also surface finish in all material is found to be smooth.

Hong, S. Y [10] investigated the consumption of liquid nitrogen to reduce its cost less than conventional cutting fluids using micro nozzle in machining of titanium alloy Ti-6Al-4V material. It result shows that micro nozzle leads to better tool life, reduced cutting forces, increases production rate at reduced cost per part and good surface finish is obtained.

Ghosh, R et al [11] investigated the cryogenic cooling during machining of hardened material using polycrystalline cubic born nitride (PCBN) and alumina ceramics ($Al_2O_3$). The results shows improvement in tool life, also productively has been significantly increases and reduced the thermal softening of tool.

Dhar, N. R et al [12] investigated the effect of cryogenic liquid nitrogen cooling during machining of plain carbon steel (C40) by varying cutting velocity and feed. The result of computational and experiment shows that the significant reduction in cutting temperature in different cutting conditions and also the cutting force reduces in cryogenic treatment as compared to dry machining.

Paul, S. et al[13] investigated the effect of cryogenic treatment of liquid nitrogen jet during turning of AISI 1060 steel on tool wear and surface finish. The experimental results are then compared with dry machining and soluble oil. The results shows the cryogenic treatment significant improve the tool life and surface finish due to reduction in cutting temperature in machining zone and favourable change in chip-tool interaction. It is also seen that soluble oil cooling does not provide any significant change in tool life.

Stewart, H. A[14] investigated the effect of cryogenic treated carbide tool and untreated carbide tool in machining of medium density fiberboard(MDF) material on tool wear. The result shows that cryogenic treated carbide tool wears out less as compared to untreated carbide tool. The result also shows that there is increase in the value of cutting force (25-30%) in untreated carbide tool as compared to cryogenic treated carbide tool.

Khan, A. A., & Ahmed, M. I[15] modified the tool to supply the cryogenic coolant through micro drilled in the tool directly in the machining area during the machining of SS using carbide tool. it is found that tool life increased by 4 times compared to conventional cooling system.

Yong, AYL et al [16] investigated the effect of cryogenic treated tungsten carbide and untreated tool during high speed milling in machining of medium carbon steel on tool wear. It is found that cryogenic treated carbide tool shows better results in term of wear resistance as compared to untreated carbide tool.

Dhananchezian, M., & Kumar, M. P[17] investigated the effect of liquid nitrogen cryogenic cooling on response parameters as cutting force, cutting temperature, chip breaking and chip thickness during orthogonal cutting of aluminium 6061-T6 alloy at different cutting parameters and it is compared with dry machining condition. The result shows that cutting temperature is reduced by 27-40%, cutting force is increases to maximum of 13% and maximum chip thickness deviation increase by 25% over dry machining.

Pusavec, F. et al[18] investigated the effect of cryogenic machining on surface integrity as function of depth is analysed. The result shows that the cryogenic treatment improves the surface integrity such as surface roughness, surface hardness, residual stress, cracks etc and thus final quality of surface is improved.

**Table 1:** Applications of cryogenics in machining environment**.**

| Author | Workpiece | Methodology | Tool used | Result |
|---|---|---|---|---|
| Wang, Z. Y et al[1999] | Reaction bonded silicon nitride(RBSN),tantalum,inconel alloy, Titanium alloy | Liquid Nitrogen(LN 2) | Cemented carbide | 1. Reduction in cutting zone temperature.<br>2. Hot hardness of tool remains intact.<br>3.Good surface finish |
| Hong, S. Y[2001] | titanium alloy Ti-6Al-4V | Liquid Nitrogen(using micro nozzle) flow are 40Kg/hr | Tool insert CNMA432-K68 | longer tool life,. better chip breaking and handeling,.high productivity, Lower production cost, good surface finish, safe to operate. |
| Ghosh, R et al[2003] | Hard ferrous materials(52100 bearing steel and A2 tool steel) | Liquid nitrogen (LIN) | polycrystalline cubic boron nitride (PCBN) and alumina ceramic(Al2 O3) | Tool life increases in cryogenic cooling as compared to flooding and dry operation. |
| Dhar, N. R et al[2002] | Plain carbon steel(C40) | Liquid nitrogen (LIN) | Carbide(SNMG120408-26TTS) and (SNMM1204 08TTS) | 1. Significant reduction in cutting temperature<br>2. Reduction in cutting forces. |
| Paul, S. et al[2001] | AISI 1060 steel | Liquid nitrogen (LIN) | SNMG120408-26TTS and SNMM120408 TTS | 1.significant improve the tool life and surface finish<br>2. Soluble oil cooling does not provide any significant change in tool life. |
| Stewart, H. A[2004] | medium density fibreboard(MDF) | Cryogenic treatment | Cryogenic treated carbide tool | 1. Tool wear reduces in cryogenic treated carbide tool.<br>2. Increase in force magnitude in the order of 25-30% with untreated carbide tool. |
| Khan, A. A., & Ahmed, M.[2008] | Stainless steel | Liquid nitrogen | Coated carbide tool | Tool life increased by 4.87 times than conventional cooling system. |
| Yong, A. Y. L et al[2007] | medium carbon steel | Liquid nitrogen | Cryogenic treated carbide tool | Good wear resistance seen in cryogenic treated tungsten carbide tool as compared to untreated carbide tool. |
| Dhananchezian, M., & Kumar, M. P[2010] | Aluminium 6061-T6 | Liquid nitrogen | uncoated carbide insert | 1. Reduction in cutting temperature by 25-40% as compared to dry cutting.<br>2. cryogenic cooling increased cutting force to a maximum of 13% over dry machining<br>3.reduces chip thickness and increases shear plane angle in cryogenic cooling. |
| Pusavec, F et al.[2011] | Inconel 718 alloy | Different cooling conditions | carbide insert CNMG120404 | 1. Cryogenic provide good surface finish.<br>2. Cryogenic machining provides higher hardness on the surface.<br>3. Fine microstructure in final part with cryogenic treatment. |

**5. Discussion and conclusion**

Cryogenic machining is a suitable environment friendly candidate that replaces the conventional cooling system that poses serious threat to the environment in terms of difficulty in its disposal. Cryogenic machining has a biggest impact on machining performance and it helps to improve the various essential parameters in machining such as tool life, , surface finish, surface integrity, microstructure ,improve the surface integrity and also cryogenics help to reduce the parameters such as power consumption, cutting temperature, cutting force etc. Cryogenic cooling encourage the researchers to machine high strength to weight ratio material such as titanium alloy, inconel etc which found extensively being used in aerospace applications, automobiles and bio medical applications. Also the cryogenic cooling system is not fully accepted in metal cutting industries owing to handling and storage issue associated with cryogenic medium. It is concluded from the above literature that cryogenic machining is sustainable approach and environmental friendly and can reduced the cost associated with other alternative methodologies such as flooded cooling, cost of coating over the tool and can be effective in machining of difficult material such as titanium alloy etc. Although cryogenic machining is more than 20 years old, this technique is not widely accepted by metal cutting industries. A general guideline for selection of cryogenic machining parameters is crucial in order to promote cryogenic turning to machine shops.

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