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A REVIEW OF CRYOGENICS BASED MANUFACTURING PROCESSES

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Abstract- Cryogenics is the science and technology associated with generation of low temperature below 123K. In engineering application, cryogenics is study of behavior and production of the materials at very low temperature and properties of material changes when cooled to cryogenic temperature. During the machining operation cooling is important aspects and many operations which cannot carried out effectively without cooling. In this review paper we focus on the effect of cryogenics fluids like liquid nitrogen (LN2) and CO2, in the material removal operations of manufacturing processes and its effects on workpiece material and tool materials properties, also observed the effect of cryogenic treatment and cooling in tool life and tool wear, cutting temperature, surface roughness, dimensional accuracy and cutting forces. As the result, Application of cryogenics treatment and cryogenic cooling in the machining processes increases the tool life and improved the surface roughness, it is also decreases the machining surface temperature, power consumption during the operation and thus tool wear decrasese and production rate increases.

keywords— Cryogenic treatment, Cryogenic cooling, Liquid nitrogen, Manufacturing process, Tool life, Surface roughness

I. Introduction

The word “Cryogenics” comes from two Greek words– “kryos” meaning extremely cold and “genes” meaning to produce.Cryogenics is the science and technology associated with generation of low temperature [1]. In Engineering, cryogenics is study of behavior and production of the materials at very low temperature and how the properties and structure changes of materials due to this. Cryogenics treatment is the methodology of ultra-low temperature processing of materials to enhance their desired metallurgical properties The treatment of the cryogenic processes are operated in three main stages as shown in fig.1 Cooling stage, the material are cooled from ambient temperature to cryogenic temperature during the time period. Soaking stage, it was stated that the soaking time in which the material is subjected to stay in the cold or cryogenic temperatures. Warming and tempering, tempering is usually performed after cryogenic treatment to improve impact resistance of treated materials [2].

Cryogenic treatment processes are not all about the treatment of surface, it affects the entire mass of the tool or component being treated, and making it stronger throughout, Cryogenic hardening is the process where at or below 123K temperature, we treat material to strengthen and increasing the grain structure of metal [3], Cryogenic machining is the machining process where the conventional cooling fluid like water, oil is replaced by a jet of either LN_2 or pre-compressed CO_2 [4], Cryogenic deflashing is a deflashing process that uses

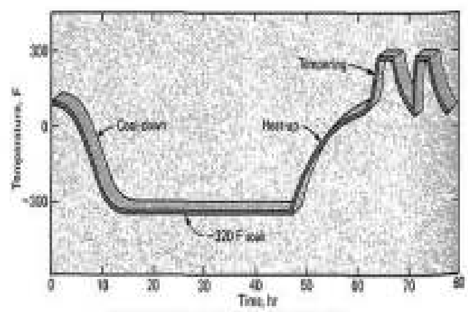

Fig.1.Typical cryogenic treatment cycle [2]

Cryogenic temperatures to aid in the removal of flash on cast or molded work pieces, cryogenic deburring is a cryogenic process used to remove burrs and flash from plastic and die cast work pieces. The low temperatures (approximately −195 °C) are achieved using liquid nitrogen, liquid carbon dioxide, or dry ice [5], Cryogenic rolling is the process when rolling carried out at cryogenic temperature, and combination of cryogenic rolling with warm rolling produced more noticeable improvement in the mechanical properties [6].

At low temperatures, properties of many metallic materials such as yield and tensile strength, hardness, wear and fatigue resistance are all enhanced in comparison with the properties at room temperature [29]. In general, materials with a face-centered cubic lattice keep their ductility at cryogenic temperatures, whereas body-centered cubic and hexagonal-closed packed materials become brittle.

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	Effects of the cooling and lubricating strategy	Flood (emulsion/oil)	Dry (compressed air)	MQL (oil)	Cryogenic (LN_2)	Hybrid (LN_2 + MQL)
Primary	Cooling	Good	Poor	Marginal	Excellent	Excellent
	Lubrication	Excellent	Poor	Excellent	Marginal	Excellent
	Chip Removal	Good	Good	Marginal	good	Good
Secondary	Machine Cooling	Good	Poor	Poor	Marginal	Marginal
	Workpiece Cooling	Good	Poor	Poor	Good	Good
	Dust/Particle Control	Good	Poor	Marginal	Marginal	Good
	Product Quality (Surface Integrity)	Good	Poor	Marginal	Excellent	Excellent
	Sustainability Concerns	Water pollution, microbial infestation, and high cost	Poor surface integrity due to thermal damage	Harmful oil vapor	Initial cost	Initial cost, oil vapor

Fig.2.Effectiveness and application of various cooling and lubricating strategies. [31]

Furthermore, component properties such as dimensional stability increase, while residual stresses decrease [30]. At low temperature Material properties knowledge and there effects at low temperature is essential to construction for a specific cryogenic applications, For example during experiments it found that when rubber quenched in to liquid nitrogen (LN_2), it become extremely hard and show the brittle behavior means broke like brittle material. Mechanical properties like ultimate and yield strength of material increase with decreases in temperature because at low temperature there is a less thermal vibration of atoms means the material vibrate less vigorously with less thermal agitation. At low temperature high value of stress in required to stretch the materials so fatigue strength increases as the temperature is lowered [7].

The impact strength of material depend upon the crystal lattice structure at low temperature, materials those shown S transformation (DBT) cannot be preferable for cryogenic applications, in generally the ductility of material decreases with decreasing in temperature.

Cryogenic machining in manufacturing process like turing, grinding processes etc. extensively and reported on the benefits of tool-life, surface finish, dimensional accuracy and residual stresses on a range of steels as shown in fig.2 that we can adopting of different strategies of cooling and treatment during the manufacturing process.

II. Literature review

Cryogenic in machining processes with their effect on the how the properties of material changes and observations on the material removal rate, tool wear rate, surface roughness and microstructure changes have been studied.

Cryogenics in material removal processes:

Cryogenic cooling and treatment applications in machining studies have been examined in turning operations even though there were its applications in other machining operations such as grinding [8], drilling [9] and milling [10] etc.

Khare and Agarwal [11] have worked on the optimization of machining parameters like cutting speed, feed rate, depth of cut and rake angle to study the surface roughness of material AISI 4240 under the cryogenic condition with the help of Taguchi Technique. In this experiment they used Liquid Nitrogen (LN_2) cryogenic fluid for the treatment of the tool and work piece as a coolant because LN_2 non-hazardless and it improve hardness and toughness of material.

Sartori et al. [12] have worked on the implementation of different lubricating/cooling strategies during machining operations in order to improve the machinability of these alloys as well as increase the tool life. The Ti6Al4V ELI titanium alloy was used in the experimental investigation. They took a fix parameters of cutting speed, feed rate and depth of the cut and apply different strategies for cooling like LN_2, Co_2, wet, dry, and mixing of theses and analysis the wear of the tool. They got results and conclusion like when applying low-temperature coolants the crater wear was drastically reduced, preserving the tool cutting edge geometry with a significant improvement of the machined surface roughness. The hybrid strategies combining LN2/MQL and CO2/MQL guarantee the advantages of cratering phenomenon and flank wear.

Kumar et al. [13] have been investigated the effect of tool wear in the copper-tungsten electrode after doing Deep Cryogenic treatment of tool and machining the work material Ti-5Al-2.5Sn alloy during Electro Discharge machining. By varying various process parameters namely cryogenic treatment of electrode material, peak current, pulse on & off time and flushing pressure and observed the rate of tool wear. The purpose was this experiment to improve the efficiency of EDM and reducing tool wear rate. As the temperature is reduced during cryogenic treatment, thermal vibration of atoms become weaker resulting in easy movement of electrons in a metal which increases the electrical conductivity of electrode. This reduces the bulk electrical heating of metal. This leads to quick removal of heat from the surface of electrode thereby reducing the TWR.

Choudhary et al. [14] have worked on the performance of tool electrode and the surface finish of material Hastelloy C-4 during the Electro Discharge machining. They observed the performance and surface structure of cryogenic tool electrode and non-treated tool in EDM process. In this study tool polarity, current pulse on time and voltage were used as input parameters. The study concluded that copper as a tool electrode shows good response towards MRR and Surface roughness was also found to be increase with increase in current. This is due to when the current increases discharge energy transferred to work piece also increases that removes material with large craters. They got from the experiment Minimum surface roughness at 4A current, 100µs pulse on time, 47µs pulse off time by non-treated copper tool electrode.

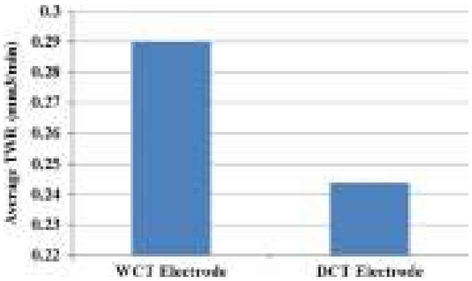

Fig.3. Difference between TWR for WCT electrode and DCT electrode.[13]

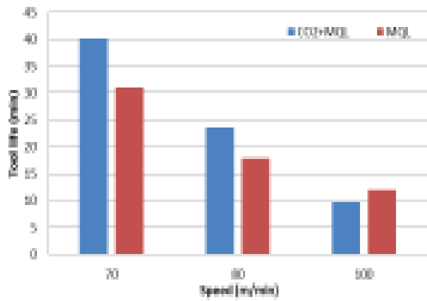

Fig.4 .Comparison of tool life achieved using MQL versus CO2[16].

Goyal [15] worked on material removal rate and surface roughness of Inconel 625 super alloy by cryogenic treated and non-treated zinc coated tool electrode in wire electro discharge machining, a wire about 0.05–0.3 mm used as a tool electrode and de-ionized water as dielectric. They took Tool electrode (normal and cryogenic), current intensity, pulse on time, pulse off time, wire feed and wire tension as a process parameters and did study about theses parameters responses on material removal rate and surface roughness. In this study found that MRR increases by cryogenically treated tool electrode as compare to normal tool electrode and that current, pulse on time and cryo-treated tool are the most influencing parameters for MRR and surface roughness.

Tapoglou et al. [16] investigated of tool life when milling aerospace grade titanium (Ti-6Al-4V) under different coolant delivery options. Tool wear progression was recorded for the following coolant options: cryogenic CO2, emulsion flood cooling, dry machining, cryogenic CO2 combined with air or MQL as well as MQL alone. The best performance at 100 m/min was achieved using flood emulsion coolant, which easily achieved a tool life of 30 minutes. The best performing cryogenic method was CO2 plus MQL which achieved a tool life of 18.5 minutes in equivalent testing.

Mia et al. [17] investigated the optimization of milling process parameter under the use of cryogenic cooling means supply liquid nitrogen through AISI 1060 steel tool. The cryogenics are comparatively cleaner because of not including disposable liquid after use.The hardened steel has been selected in this study due to its wide application in the locomotive, aircraft, tool and die industries. Cryogenic cooling effect provide to through-tool and cutting oil at machining area. They got results that the cutting conditions i.e. use of coolant and its application method plays dominant role in defining the value of surface roughness, cutting force and specific cutting energy.

Sadik et al. [18] have investigated and understood the wear mechanisms that determine tool life for PVD-coated and uncoated tools in face milling of Ti-6Al4V over a relevant range of cutting data in cryogenic (CO2) and wet conditions. In this work consist of face milling of a titanium alloy with coated and uncoated carbide tools under different cooling conditions and cutting data. The cryogenic coolant CO2 can provide up to 6 times increase in tool life compared to conventional emulsion with in an appropriate window of cutting data.

Reddy et al. [19] have worked on the grinding machining with the application of LN_2 as a coolant to on the surface grinding of hardened AISI 52100 steel using alumina abrasive wheel. They got conclusion on the investigation that Power consumption in application of cryogenic jet is almost 2 and 2.5 times than dry and conventional soluble oil respectively at the given grinding condition. Grinding ratio results clearly depicts the substantial improvement in wheel life under cryogenic environment compared to dry and soluble oil condition. Liquid Nitrogen is extremely effective in controlling grinding zone temperature, its adverse effect has been realised in terms of high spindle power consumption and significant dimensional inaccuracy

Schoop et al. [20] investigated the material Ti-6Al4 V alloy was machined using polycrystalline diamond (PCD) tools under three different cooling/lubricating environments: cryogenic cooling (liquid nitrogen), hybrid cooling/lubrication (LN2 and oil based MQL-minimum quantity lubrication) as well as conventional flood cooling (emulsion) to achieve the better machining performance and reduce tool wear. They have gotten conclusions that tool-wear under conventional flood cooling was more than 4–5 times higher compared to both the cryogenic and hybrid conditions and Surfaces produced by cryogenic machining exhibited the lowest roughness when the tool was new.

Cryogenics in metal forming processes:

Cryogenics treatment in metal formimg processes applications to common in the manufacture of forging dies and other kind of tools [11], improvements in the formability, strength and surface quality of sheet via cryogenic sheet metal forming [28], CR process can effectively improve the tensile strength and yield strength of Al alloy through significantly enhanced dislocation strengthening and grain boundary strengthening [13].

Shi et al. [21] have investigated the microstructure, mechanical properties, annealing behavior and post-annealed microstructure/properties relationship of work piece material of 5052 Al alloy by the cryogenic rolling (CR). They got information after analysis that Compared to Room Temperature Rolling processing, the Cryogenic Rolling process can effectively improve the Tensile Strength and Yield Strength of 5052 Al alloy through significantly enhanced dislocation strengthening and grain boundary strengthening and the post-annealed, also improve the Tensile Strength and Yield Strength of the Cryogenic process for 5052 Al alloy were ~30 MPa higher than those of the Room temperature rolling process.

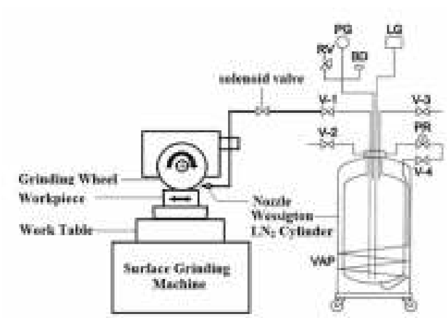

Fig.5. Cryogenic grinding setup [19].

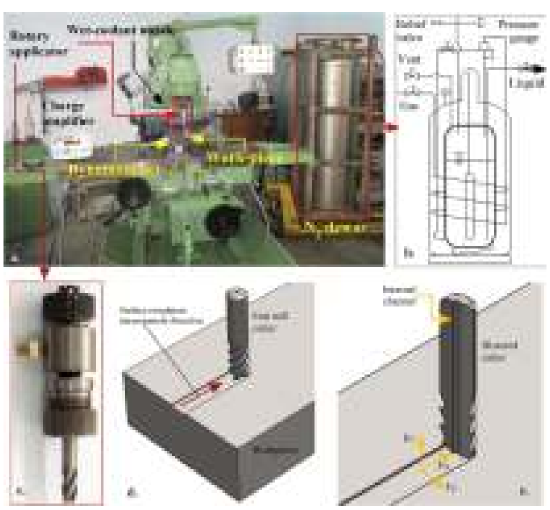

Fig.6. (a) Experimental setup (b) schematic of used LN2 Dewar (c) specially designed and fabricated rotary applicator for supplying liquid N2 as through-tool (d) schematic of cutter-work (e) schematic of bisected cutter

Abbasi-Baharanchi et al. [22] investigated the material Al6061 alloy was by the cryorolled up to 85% thickness reduction and observed the effect of the cryorolling process on its microstructural, mechanical and tribological properties.They performed the experiment like that before cryorolling, the Al6061 alloy solution was treated at 530 °C for 3 h followed by water quenching to room temperature. The samples were dipped in liquid nitrogen for 20 min before the first rolling pass and 5 min prior to each rolling pass during the cryorolling process. They got result that by applying the cryorolling process on Al6061 alloy, dislocation density increases due to the suppression of dynamic recovery during rolling. As a result, tensile strength and hardness of the CR sample will increase.

Kumar et al. [23] investigated the cryogenic sheet metal forming behaviour of AW-6016-T4 sheet. In this they did work on AW-6016-T4 sheet is characterized over the temperature range from −196 to 25 °C by uniaxial tension and Nakazima tests to investigate the forming behaviour. Cooling of the samples was performed by spraying liquid nitrogen into the chamber until the desired sample temperature was reached. Cryogenic forming has shown improvement in both the strength and part quality. A maximum depth of 6 mm was obtained during forming at RT while a maximum depth of 8 mm was reached during cryogenic forming at −150 °C. This study has demonstrated the potential of cryogenic forming for manufacturing complex automotive components.

Singh et al. [24] investigated impact of cryogenic treatment on AISI D2 steel blanking punch and evaluated in terms of tool life, part quality and pecuniary gain. The increase in hardness and wear resistant of AISI D2 blanking punch after cryogenic treatment. The cost of about 3.5% of annual turnover was saved and approximately 60% production rise was reported after the cryogenic treatment of the AISI D2 blanking punch. The use of liquid nitrogen for cryogenic treatment of blanking punches is environmental friendly and non-hazardous.

Cryogenics in fabrication processes:

Lin et al. [25] worked on the investigation on the effect of post-weld heat treatment (solid solution + artificial aging) on the microstructure and cryogenic fracture toughness of the weld metal of VPTIG welded AA2219 joints were investigated by using crack tip opening displacement (CTOD) test method. First, solution treatment was conducted at 535 °C for a soaking time of 90 min with water quenching. Then, artificial aging treatment was carried out at 175 °C for a soaking time of 12 h with furnace cooling. The strength, plasticity and fracture toughness at 77 K were superior to those tested at 298 K. For sample A, the tensile strength, elongation and CTOD value at 77 K were 36.7%, 46.9% and 18.5%, respectively, higher than those at 298 K. For sample B, these properties at 77 K were 24.8%, 52.4% and 19.6%, respectively, higher than those at 298 K.

Bartolomé et al. [26] worked that 3D printed objects in ABS (Acrylonitrile Butadiene Styrene) can be used at cryogenic temperatures, offering flexible solutions in different fields. ABS is a thermoplastic with a low glass transition temperature that solidifies quickly, and presents medium strength and performance at reasonable prices, they reported a thermo mechanical characterization (tensile tests and thermal compression) of 3D printed ABS probes at 77 K. These tests served to delimit the maximum permitted stresses and, therefore, the type of applications where 3D printed objects may be used safely.

Zhisheng et al. [27] have investigated the deep cryogenic treatment technology in the treatment of electrodes, for spot welding hot dip galvanized steel plate and electrode, life experiment is carried out. The microstructure and elements distribution of the deep cryogenic treatment electrodes, and non-cryogenic treatment of electrodes for spot welding hot dip galvanized steel is observed by, scanning electrical microscope and X-ray diffraction. The experimental results shows that deep cryogenic treatment makes Cr, Zr, in deep cryogenic treatment of electrodes. They observed that soundness of deep cryogenic treatment electrodes for spot welding galvanized steel is higher than that of non-deep cryogenic treatment electrodes. Many Cr and Zr particles, whose distribution is diffusive appears in the basal body after deep cryogenic treatment. Grains of deep cryogenic treatment electrodes are finer than that of non-deep cryogenic treatment electrodes and Electrode life is improved obviously from 550 to 2234 welds by deep cryogenic treatment.

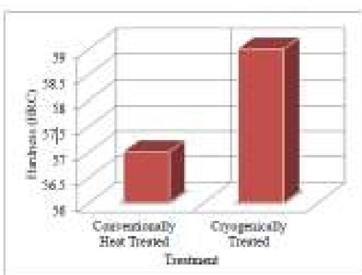

Fig.7. Hardness of conventionally heat treated and cryogenic treated specimens [24].

III. Conclusion

It is observed by researchres that due to the application of the cryogenic treatment in the turing we improve the surface quality of the workpicece by the optimum process parameters.The hybrid strategies combining LN2/MQL and CO2/MQL guarantee the advantages of reduce the tool wear and provide better cooling effects during the machining processes.Deep cryogenic treatment have advantage in advance machining process like electro discharge machining and wire electro discharge machining to improve their material removal rate and reduce the tool wear rate and also get the good surface finish by the optimization of the process parameters.In the surface grinding process liquid Nitrogen is extremely effective in controlling grinding zone temperature and dimensional inaccuracy.Cryogenic cooling with LN2 has been shown to not only improve tool-life but also produce desirable surface integrity characteristics, such as compressive residual stresses, super-hard, nano crystalline surface layers and improved corrosion resistance.Cryogenic Rolling process can effectively improve the Tensile Strength and Yield Strength alloy material. Through tool cryogenic cooling by liquid nitrogen is more effective than dry cutting and conventional cutting oil applied end milling.

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