Cryogenic assisted machining of hard to cut materials: A Review

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ABSTRACT

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Machining processes have undergone lot of changes over the last several years to improve the quality and productivity. There are several important problems, faced by machinists when machining so called 'difficult-to-machine' materials, which includes metals, alloys, composites, rubber, refractory materials etc. These include excessive tool wear, temperature, severe work hardening, chip formation and breakage, bad surface finish and surface integrity. Cryogenic cooling is a relatively new cooling technique explored by researchers and industries all over the world to machine these materials and reduce the associated problems. There has been lot of research articles available in this domain. In this regard, this paper reviews research articles published during 2000 to 2018, with focus on introduction of cryogenics to machining, some details of difficult to machine materials, effect of cryogenics on surface finish, tool wear, chip formation and breakage, microstructure and hardness. About 108 articles have been reviewed and salient conclusions are drawn at the end of the paper, which establishes the fact that cryogenic machining is going to be an important machining technique, which will be adopted by industries to produce better quality products from machining of these materials and promote 'sustainability in machining'.

1. Introduction

"Excessive heat generation, friction and wear between the tool and workpiece are common problems in metal cutting processes" [1]. Therefore, since the beginning of 20th century, use of cutting fluids is significant to cool and lubricate workpiece and tool, to eradicate above problems. The important functions of cutting fluids could be summarised as follows [87, 96].

- To carry away enormous amount of heat generated during machining.
- To carry away foreign particles generated because of abrasion.
- To produce thick film lubrication between contact surfaces.
- To act as corrosion inhibiter.
- To limit chemical diffusion between the tool and workpiece.

Different cooling/lubricating methods i.e. high-pressure coolant [91, 93], flood cooling [18,97] and Minimum Quantity Lubrication (MQL) [95], air jet cooling [88], and cold-water jet mist cooling [89] have been studied by different researchers to improve machining processes. Flood cooling is one of the oldest methods used by the industries, where copious amount of cutting fluid is fed towards the cutting zone. In most cases, significant amount of cutting fluid do not flow to the cutting point is left unused [68, 71]. The concept of sustainability is to be created and consolidated at all levels namely social, economic and environmental levels. To satisfy this requirement in machining processes, study of lubrication and its consumption during machining is very important. A survey of consumption of lubricants in machining applications suggest that, almost 16% of total cost [85] is related to use of cutting fluids and in case of hard to cut materials, it reaches up to 20-30% [1]. The management of these fluids by the human operator is causing several health problems such as, skin irritation, loss of pulmonary function, acne, pneumonia and even lung or skin cancer [82, 87]. Therefore it is argued

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by most of the researchers that utilization of cutting fluids during machining is wasteful financially and causes significant damage to the earth [70].

Minimum quality lubrication (MQL) is found to be one of the alternatives to the conventional system. This technique consists of spraying aerosol, which can be biodegradable oil micro-particles at the tool work interface. The flow rate of these oils is generally very less and is between 10 ml/h and 100 ml/h, therefore oil consumption is reduced by around 1000 times [95]. MQL provides better thermal stability and lubricating properties compared to flood cooling system [96]. Yogie Rinaldy Ginting et al. compared flood cooling and MQL technique during machining of AISI 4043 steel and reported that MQL was feasible as an alternative to flood as it provides better lubrication and cooling [33]. Armando Marques et al. analysed the surface integrity during turning of Inconel 718 using solid lubricants dispersed in neat oil delivered by MQL and reported that significant microstructural changes and changes in tool life and surface finish can be obtained by addition of solid lubricants in MQL [34]. Significant amount of heat is generated while machining hard materials. The oil particles get evaporated before reaching the cutting zone and thereby giving bad smell [29]. To improve this problem, the oil is mixed with water and passed to the cutting zone.The presence of water helped in carrying the lubricant, spreading the lubricant and cooling the cutting zone due to its high specific heat and evaporation [30]. Despite many advantages, at the end of machining process, the disposal of lubricant is still creating many problems. Because of strict rules against environmental pollution and increased consciousness concerning environmental impact from the industries, the focus has been towards development of environmentally friendly cryogenic machining techniques [94].

This paper surveys 108 papers published in the field of cryogenic machining, especially considering hard to-machine materials. The use of cryogenic machining has been increasing over the last several years, as use of this method of cooling reduces tool wear, temperature, improves surface roughness and integrity. Further it avoids all problems associated with flood cooling, which is a conventional cooling method and supports 'sustainable machining'. This review covers some important aspects like use of cryogenics for treating tool inserts, the commonly machined difficult-to-machine materials and effect of cryogenic cooling on surface topography, tool wear, chip morphology, microstructure and hardness. This review does not claim to be all comprehensive, but tries to objectively review research papers from 2000 to 2018, with more papers reviewed in the time span 2010-2018.

1.1 Introduction to cryogenics in machining

Cryogenics is the study of low temperature, which begins at temperatures underneath 120 K (~ -150 °C) and which plays a major role in modern industrial science. Since 1950, use of cryogenic fluids to remove the heat during machining has started [46]. The cryogenic cooling system can be classified based on cryogenic fluids as shown in figure 1. The primary purpose of cryogenic coolant is to diminish the temperature produced during cutting process, modify the frictional characteristics between tool-chip-work interface and change properties of the work and the tool material [71].

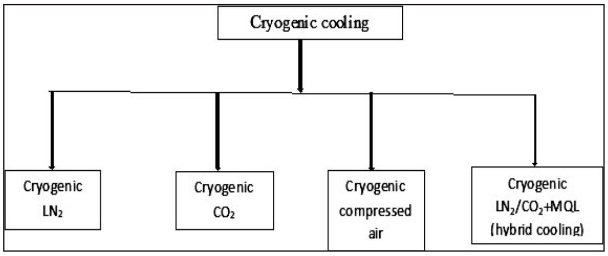

Fig.1. Cryogenic cooling systems.

Liquid nitrogen (LN_2) is to a great extent utilized as cryogenic coolant in machining, as nitrogen is protected, non-destructive and non-ignitable. Also, most of the machining processes expect transparency under the application of cutting fluid to view the actual cutting mechanism, which can be achieved using liquid nitrogen. 78 % of the air comprises of nitrogen and health risks on operator due to its usage during machining is less [70]. The melting and boiling point of nitrogen are 633 and 774 K (-210 and -196 °C) respectively. Usually liquefaction of air is used to produce liquid nitrogen, due to a transformation from the gaseous phase to the liquid phase. Most of the research work has proved that LN_2 can be used effectively for reducing heat generation during machining of hard metals or during hard turning [47, 71, 98]. During machining, LN_2 demonstrates various useful properties compared to ordinary cutting fluids. It has very low viscosity and will evaporate quickly and hence to maintain it between contact surfaces [77]. Despite many advantages, the problem with LN_2 is creation of a very low temperature environment (-196^{0}C), which will pre-cool the work piece and increases the cutting forces during machining [78].

Hence some researchers have tried machining using CO_2, which can generate a temperature of -78^{o}C. But it is a green house gas, which will pollute the environment and hence its uses are limited [78]. A few analysts have like wise attempted the utilization cryogenic air and cryogenic air mixed with MQL (C--AMQL) cooling/ lubricating strategies in hard machining [76]. Many companies have tried the cold compressed air and observed varying degree of success in replacing traditional cooling systems [81, 85].

Turning involves heat generation due to chip formation in the primary shear zone and due to friction between the tool and chip in the secondary shear zone and cooling of both these zones is essential to improve machining characteristics [23, 63]. There are different possibilities of applying or directing the cryogenic fluids in the cutting zone i.e. to the rake face [19], flank face or both rake and flank faces [14,73]. Many researchers have tried these possibilities.

The use of cryogenic fluid in machining processes can be analysed under different heads namely, chip cooling, precooling of work piece and tool, indirect cooling of the tool and jet cooling by injecting the fluid into the cutting zone. Depending upon the work material, tool material and cutting conditions, many researchers recommended that cryogenic jet cooling was effective, which lowered the temperature by removing 10 to 35% of total heat [92].

2. Cryogenic Treatment of Tool Inserts

Many researchers have investigated treating the inserts under cryogenic condition for specific period of time and used it in machining process and observed the results. Sitki Akincioglu et al. [57] gradually cooled and heated tungsten carbide inserts under controlled condition to prevent potential micro-cracks in tool. The tool was slowly cooled to −80 and −145 °C in 6 h and held in this condition for 24 h. Further, brought down to room temperature in 6 h and tempered at 200°C for 2 h to remove stresses due to cryogenic treatment. Simranpreet Singh Gill et al., [67] treated tungsten carbide inserts using deep and shallow cryogenic treatment to machine hot-rolled annealed steel stock. The deep cryogenic treated insert gained more cutting life, when compared to shallow cryogenically treated inserts. Hui-Bo He et al. [69] cryogenically treated TiAlN coated YT15 tungsten carbide inserts at -196^{0}C for 30 h and turned 40Cr steel under cryogenic cooling. They concluded that tool life of cryogenically treated tool was about 60 min, whereas in case of coated and noncoated inserts, under no cryogenic condition it was about 50 min and below 30min respectively. A. Palanisamy et al. [79] cryogenically treated the multi-layered CVD-coated tool in LN_2 for 24 hrs and then tempered at 200° C for 2 hrs. There was a 5–6% improvement in hardness measured using Vickers micro hardness tester.

T. V. Sreerama Reddy et al. [80] compared the untreated and deeply cryogenic treated P-20 tungsten carbide inserts in turning of C45 steel. The insert was gradually cooled to -176^{o}C at the rate of 2^{o}C/min, held at that temperature for 24h and then to room temperature at the same rate. They have observed that at room temperature, hot hardness of cryogenic treated insert was less than that of the untreated insert. However, as temperature increased hot hardness of cryogenic treated insert increased, which overtook the hot hardness value of untreated insert. In another study by the same authors, turning experiments on AISI 1040 work piece was carried out using deeply cryogenic treated P-40 tungsten carbide inserts. Cryogenically treated inserts successfully lessened the tool flank wear, as cryogenic treatment would harden the tool material [42].

3. Difficult to Cut Materials

Machinability of materials mainly decides, whether the material is difficult to cut or not. Difficult to cut materials generate excessive heat during machining and thereby result in high temperature environment, excessive tool wear, difficulty in chip formation, poor surface quality and high power consumption. The main reason for this is low heat dissipation due to relatively low heat conductivity and high material strength and hardness [10]. There are different categories of materials, which are considered as difficult to machine materials and include refractory metals and super alloys, consisting of titanium, nickel, steel, chromium, molybdenum, cobalt, tungsten magnesium, tantalum alloys etc. [105].

3.1 Titanium (Ti) alloys

Titanium is the fourth most abundant material in the earth, which is soft in its purest state [10].

At low temperature, pure titanium is allotropic with hexagonal close packed (HCP) crystal structure (α phase) and a body centered cubic (BCC) structure (β phase) above 882°C. Titanium alloys are one of the super alloys, exhibiting complex deformation mechanism during cutting process, which is very different from conventional metals. Ti-6Al-4V, representing α+β alloys, is widely used in aerospace, which is about 50% of total titanium used. The yield strength to tensile strength ratio is more than 0.9 and flow stress increases gradually, when strain rate is greater than 10^3 /s. The adiabatic shear band and growth of crack produces segmented chips, which varies the chip thickness. The low elastic modulus of work piece causes the workpiece to deflect sideways, away from the tool, which results in chatter and vibrations [8,71]. Ti-5553 (Ti-5Al-5Mo-5V-3Cr) is another newly developed beta Ti alloy, which is mainly used in aircraft industry for landing gear, because of its higher yield strength, good hardenability and excellent fatigue crack growth resistance. The machinability of this alloy is not being studied widely as other alloys [74].

The properties which are responsible in making titanium alloys, hard to cut materials can be summarized as follows [10, 32, 58]:

- Lower thermal conductivity and higher thermal capacity
- Austenitic structure, exhibiting high strain hardening
- Low elastic modulus
- Higher dynamic shear strength
- High chemical reactivity with tool materials causing galling, welding, and smearing problems.
- Short contact length between chip and the tool causing high cutting temperature and stress in the cutting zone.
- Deflection of work piece causing chatter and vibrations during cutting.
- Creation of serrated chips, which is partially responsible for severe flank wear.

3.2 Nickel based alloys

Nickel and nickel-based alloys, in particularly Inconel 718 are extensively used in aircraft, chemical, marine and automotive industries [99]. The alloying elements used with nickel belongs to ‘d’ block of the periodic table such as chromium, titanium, cobalt and aluminium, as well as small amounts of carbon, boron and zirconium [107]. At elevated temperature, it shows high resistance to mechanical and thermal shock, mechanical and thermal fatigue, creep, corrosion and erosion. Because of work hardening capacity and poor thermal conductivity (11 W/mK), it will generate high stresses and temperature during machining [9, 19]. The presence of hard carbide phase in the alloy is main reason for abrasive wear of tool and also high ductility of these alloys results in adhesion tool wear [62]. Inconel 718 consists of gamma and gamma prime phase in presence of carbides and metal precipitates. This gamma phase is a continuous matrix in a face centred-cubic (FCC) structure. This good strength of the material increases temperature up to 827°C during machining [108]. The properties making Nickel based alloys, a difficult to cut material can be summarized as follows [11, 17, 28, 90]:

- High heat generation during machining.
- Vulnerability to form built-up edges and to work harden.
- Excessive tool wear because of high mechanical and thermal load on tool during machining.
- Presence of hard carbide particles encourages abrasive tool wear mechanism.
- Higher chemical affinity towards cutting tool, results in elevated diffusion and adhesion wear.
- Higher strain rate sensitivity and hot hardness.

3.3 Other materials

- ***Elastomers:*** These are group of difficult to cut materials, which are usually produced by injection moulding and not by cutting processes. Because of low elastic modulus and higher elongation, these materials will result in higher elastic deformation before fracture due to the cutting force. Elastomers possess high heat capacity, which lies above steel and lower thermal conductivity, which is lower compared to steel. Cutting forces are higher in cutting of elastomer assisted with cryogenic cooling, as elastic modulus increases at lower temperature. Also, at higher strain rates, they becomes tiffer and brittle, showing energy-elastic behaviour [22]. In order to machine elastomers, it is mainly required to achieve glass transition temperature, otherwise it is very difficult to machine, as it is prone to tearing and burning [23].

- ***Composites:*** Cutting process of composites are very different from conventional materials, because of their anisotropic properties. Metal matrix composites are widely used in automotive and aerospace applications. In aluminium based metal matrix composites, aluminium acts as matrix phase and reinforcement being metallic and harder materials such as Al_2O_3, SiC, TiC,C, TiB_2, and B_4C. The presence of hard particles adversely affects the machining process. Presence of intermittent reinforcements causes high strain and temperatures while machining, thereby causing severe plastic deformation through seizure of chips, which ultimately decreases tool life and affects the surface finish [13, 31, 101].

- ***Steel alloys:*** Steel is considered as one of easiest material to machine by most of the researchers, nevertheless some alloys of steel such as low carbon steel, hardened steel, stainless steels are considered as difficult to machine. Low carbon steels are ultra-high strength steels (UHSS) having yield strength above 1380 MPa. Some typical UHSS are: 4130, 4140, 4340, 6150, 9260, 300M and D6ac [24]. Stainless steel is usually used in aircraft fittings, jet engine parts, missile fittings, nuclear reactor components, marine constructions, oil field valve parts and centrifugal compressors. Because of low thermal conductivity of these materials, during machining lot of heat will be generated, which will reduce the tool life and surface finish [25, 70]. The presence of BUE during machining causes excessive tool wear and deteriorates the surface integrity of the work [26]. Hardened steel refers to category of steel having hardness of 40–65 Rockwell hardness at C scale (HRC). The application of this steel usually is found in extrusion and forging dies, stamping and punching dies, fuel injector nozzle, landing gears, jet engine mounting, bearing and its houses, etc. Hard machining (turning & milling) is found to be one of the alternative to traditional grinding operation, thereby gaining popularity among the researchers and industrial practitioners. Excessive tool wear is observed because of high plastic deformation of cutting tool during hard turning. High temperature generation during cutting causes diffusion wear of tool and non-uniform flank wear leading to catastrophic failure of the tool [27, 35,48, 102].

- ***Tantalum:*** Tantalum is a refractory material, has high acid resistance and it is considered as one of the noble material. The tensile yield strength of tantalum is 345 MPa and is quite ductile, however tantalum absorbs oxygen, nitrogen and becomes brittle at high temperature. Tantalum is considered as extremely difficult to cut because of following reasons:

  1. High shear strength and work hardening capacity
  2. High heat resistant because of low thermal conductivity
  3. Formation of built up edge [102].

- ***Tungsten alloy:*** Tungsten belongs to the group of hard materials, having high resistance to wear and high strength even at high temperatures. Usage of tungsten could be seen in nozzles of rockets, protective shield for space vehicles and other high temperature applications. Usually these alloys made up of two phase composites comprising of tungsten grain dispersed into low alloy melting point ductile matrix such as Fe, Cu, Ni and Co. Difficulty in machining of these metals is associated with high heat generation and high cutting forces [5].

- ***Magnesium Alloy:*** Magnesium and its alloys are low melting point alloys, mainly used in automotive, electronics and aerospace industries because of their light weight and high strength [40]. Recently AZ31 and AZ91 magnesium alloys have found their applications in biomedical implants. When temperature reaches 450 °C, they are prone to ignite due to its low melting point and also danger of explosion is expected, when particle size is less than 500 µm. The low melting point leads to melting of chips over the newly machined surface, leaving behind an unsatisfactory surface [40]. The use of cutting fluid is also limited, as they have a tendency to react with water to give highly explosive hydrogen gas, which makes the process unsafe. Whereas dry machining should be conducted under controlled cutting conditions,to control the amount of heat generation [39, 64].

4. Effect of Cryogenic Cooling on Surface Finish

With rapid development and deployment of advanced processing technologies, manufactured products are expected to have superior surface quality. The exhibition of part to handling is affected by the quality and it depends on the metallurgical and mechanical condition of the subsurface layers [91]. Surface finish is mainly affected by properties of work piece material, tool material, cutting conditions, type of machining, type of machine tool, type of coolant and cutting conditions. It was said in [57] that increase in cutting speed increases the heat production, which results in rapid deformation of work. So, it is needed to decrease the built-up edge (BUE) formation on cutting edges along with increased cutting speed to improve surface topography. [58] reported that cryogenic cooling can increase tool life, best performance visible at high flow rate and high pressure. However, surface roughness does not significantly vary under cryogenic cooling, as impingement of the same on the work piece, other than the cutting zone, alters hardness and the mechanical attributes of the material, which thus increases the requirement of cutting power.

M. N. Islam et al. [3] has studied the effect of different cooling methods on surface finish and dimensional accuracy of titanium alloy during turning. They found that various cooling methods affected circularity error and diameter error, where as it had negligible effect on surface finish. Particularly at high cutting speed (100m/min) and medium feed rate, Cryogenic cooling lessened the diameter error. And it is mainly decided by the auxiliary tool flank wear and temperature of work piece. The cryogenic cooling will benefit in reducing the temperature and there by diameter error. Dry machining and combination of medium values for feed rate and cutting speed gives optimum value for circularity due to local softening and chip formation mechanism. The topography of turned titanium alloy part was mainly decided by the feed rate and contribution of cooling method on roughness was as less as 0.16%.

In another study by Stefano Sartori et al. [6], the machinability of Ti6Al4V created by direct melting laser sintering (DMLS) was analysed. The turning experiments were conducted on as-built and heat treated DMLS Ti6Al4V at 0.1 and 0.2 mm/rev under dry and cryogenic cooling conditions. The 2D and 3D surface examination demonstrated that cryogenic cooling resulted in more discontinuous and double feed surface, which may be due to increase in ductility of materials and due to drop in temperature. The cooling method and cutting conditions influenced the surface defects and their dimensions. Highest compressive stresses were generated for both dry and cryogenic cooled conditions. Julius Schoop et al. [18] examined the machinability of Ti-6Al-4V with polycrystalline diamond tools. Three techniques namely cryogenic, flood cooling and hybrid cooling were used, steady feed rate and depth of cut of 0.01mm/rev and 0.1mm and three cutting speeds of 120, 240 and 360 m/min were used. Cryogenic and hybrid cooling methods were observed to give good surface roughness with value as low as R_a=40nm. Also tool wear was less than 10µm after 65 min of cutting at speed of 240 m/min.

Tze Chuen Yap et al. [84] studied Ti-5Al-4V-0.6Mo-0.4Fe using carbide tool K313 using low pressure liquid nitrogen. It was superior than dry machining with reference to the three surface roughness parameters i.e. R_a, R_q, and R_{max}. The decrease for these three parameters were about 11.9, 10.8, and 8.6 % separately, due to cooling by liquid nitrogen. G. Rotella et al. [45] machined Ti-6Al-4V alloy under dry, minimal quantity lubrication and cryogenic cooling conditions with coated tools at different cutting speeds and feed rates. Surface roughness values lessened with increase in cutting speed and feed rate had less impact on the roughness. For each of the three cooling conditions, it was less than 0.3 µm.

F. Pusavec et al. [98] studied surface integrity in LN_2 cryogenic machining of nickel based alloy-Inconel 718 with carbide inserts. Four different cooling methodologies were studied, dry, MQL, cryogenic and cryogenic with MQL. There was large difference in the improved values of surface finish from cryogenic to cryogenic with MQL based cooling. The improvement in surface finish was attributed to better lubricating and cooling property of liquid nitrogen. N. G. Patil et. al. [4] looked at dry and cryogenic CO_2 turning of Inconel and observed better surface finish. The roughness reduced with increment in the cutting rate for both dry and CO_2 turning. A.Iturbe et al. [19] used liquid nitrogen (LN_2) with MQL in machining of Inconel 718. The LN_2 and MQL were directed towards rake face of carbide inserts. The results revealed that surface roughness depend upon the flank wear and it increased with tool flank wear. However obtained roughness values failed to meet standard values recommended by aerospace industry (R_{tmax}=6µm; R_{amax}=1.6µm). D. Fernandez et al. [97] argued that better surface roughness can be obtained using emulsion cooling compared to cryogenic and cold air. They performed turning experiments on

Inconel 718 utilizing carbide under various cooling techniques. They observed cryogenic coolant freezing the work piece besides the cutting zone and thus hardening the work piece and hence increased the cutting forces, there by roughness. Similar results were observed in case of cold air also by them. They concluded tool wear and changes in work piece properties decide the surface roughness of machined sample.

Taghi Feyzi et al. [65] contemplated the machining of Inconel 718 with a new hybrid machining technique. A combination of three non-customary machining types namely plasma-improved machining, cryogenic machining, and ultrasonic vibration assisted machining were used and compared with conventional one. Use of cryogenic machining lessened the temperature in the cutting zone, diminished tool wear and expanded tool life, while plasma-enhanced machining increased the temperature of the work piece to make it softer. Also, the use of ultrasonic vibrations with the tool helped improve cutting quality and enhanced tool life by lowering, the cutting forces and improving the dynamic cutting stability. Under same cutting conditions a minimum R_a value of 0.2 µm was accomplished with the hybrid method, where as in conventional method it was around 2.5 µm. S Thamizhmanii et al. [21] examined the surface roughness and tool wear of titanium and Inconel 718 alloy under cryogenic condition using coated carbide inserts. The surface roughness obtained during turning of titanium alloy was low at cutting speed of 50m/min and depth of cut of 1mm in comparison to Inconel 718. However, flank wear in case of Inconel 718 was low at 1mm depth of cut than 0.50 and 0.75mm compared to titanium alloy. An un-uniform crater wear was found in turning of titanium, where as it was less deep in case of Inconel 718.

Srinivasa Rao Nandana et. al. [5] considered the machining of tungsten heavy alloy under cryogenic environment utilizing solid carbide inserts. The liquid nitrogen was made to pass on the rake face of the tool. The surface roughness under cryogenic cooling strategy was around 20% lesser, when compared with conventional water based cooling approach with 1.5 µm R_a. Z.Y. Wang et al. [2] studied the machining of tantalum under cryogenic environment using tungsten carbide material with cobalt inserts. The liquid nitrogen was passed over tool face using copper tubes. The surface roughness under regular and cryogenic cooling was observed to be 3.01 µm and 1.8 µm separately for same cutting length of 105 mm. The above results showed almost 200% improvement under cryogenic conditions compared to conventional.

5. Effect of Cryogenic Cooling on Tool Wear

Tool wear is one of serious issue in all machining processes. Tool wear basically relies on nature of work piece, nature of tool material, cutting conditions, nature of machine tool, type of machining and type of lubricating and cutting agents used [54]. Most of the researches have proved that use of efficient cooling system is very much important to enhance the tool life [96, 97, 98, 100]. Tool wear happens as a result of several tool wear mechanisms such as abrasion, adhesion, oxidation and diffusion [48,49]. In fact, abrasive wear was more prominent for harder work piece materials and adhesive wear for softer work piece [50]. The tool failure in normal or hard turning may take the form of nose wear, crater wear, flank wear, plastic deformation, chipping, built-up edge, and catastrophic breakage [55]. It was accounted for that surface quality and tool life were fundamentally decided by amount of auxiliary and principal flank wear [36, 38, 51]. Tool wear also depends upon the tool chip contact length, because interfacial friction is produced and the highest temperature frequently happens in this contact zone. Larger contact length leads to larger force to form the chip due to friction at the tool-chip interface, which increases the temperature between the interfaces [53]. Most of the researches have used LN_2 for greater tool life by diminishing the interface temperature. The enhancement of tool life is mainly dependent upon the position of nozzle with which impingement of liquid nitrogen takes place [72]. Also, many researches have shown that changing the direction and position of impingement of cryogenic coolant will alter the tool life considerably. Along with this some researches have tried MQL with cryogenic coolant to improve the tool life [99].

Despite a variety of cooling techniques and their application, machining of refractory alloys has not been markedly improved. As the temperature between tool and work changes, it changes the contact condition in the interfaces and increases the tool wear. Therefore, when using the lubricant and coolant fluid, the cutting speed must be increased to reduce the temperature [37]. During cryogenic machining, flank wear predominantly happens as a result of scouring of hard surface along the flank surface and it increments with increment in the cutting speed.The decrease in wear is due to control of abrasive and attrition wear mechanisms, through a decrease in the cutting zone temperature under cryogenic atmosphere.

A.Bordin et. al. [7] considered the tool wear mechanisms and modes for PVD covered tungsten carbide inserts, when turning electron beam melting (EBM) Ti-6Al-4V under dry and cryogenic cooling systems in semi finishing cutting conditions. Two copper nozzles carrying liquid nitrogen, inclined at an angle of 45° were sprayed towards rake and flank face of the tool. The supply pressure and mass flow rate were set to 15bar and 0.9kg/min. In summary, the main tool wear mechanism in both dry and cryogenic condition was adhesion. Nevertheless concentrated cooling capacity of liquid nitrogen successfully inhibited the sticking of the work material on tool face by providing reduction in tool-chip contact length and by reducing the thickness of tool chip contact length. Since cratering was temperature dependent, low temperature conditions prevented the formation of crater wear. The adhesion of work material on the tool face was successful in preventing the abrasion wear, but tool life did not reach satisfactory level. The cryogenic cooling condition limits the adhesion, thereby chipping off the fragments from the tool flank face.

Stefano Tirelli et. al. [12] conducted experiments to compare normal and cryogenic cooling under rough turning of titanium alloy using coated carbide tool with coating layers TiAlN (2 µm) + AlCrO (0.7 µm). It was discovered that cryogenic cooling improved the tool life for all cutting conditions. For 50 m/min and 0.2mm/rev it increased by 20% and at 60 m/min and 0.25 mm/rev it was 16%. In spite of the fact that at high cutting rate or high feed rate, LN_2 had reduced capability in reaching the cutting zone because of high temperature generation and less pressurized liquid nitrogen. S. Sartori et al. [6] researched the effectiveness of machining of Ti-6Al-4V produced utilizing two additive manufacturing techniques, in particular direct metal laser sintering (DMLS) and electron beam melting (EBM) using dry and LN_2 coolant. The experimental results showed that adhesion, abrasion and diffusion wear mechanisms were largely accountable for tool wear. The utilization of cryogenic coolant decreased the crater wear and flank wear adequately. Also alloy produced using EBM had better machinability than produced using DMLS with respect to tool wear [21]. Y. Sun et al. [15] examined the machinability of Ti-5553 alloy under different cooling systems namely MQL, flood-cooled and cryogenic. The exploratory outcomes uncovered that flank wear was found in nose region as a result of high strength work material. EDS measurements showed that adhesive wear was the essential component of nose wear. However it reduced significantly under cryogenic cooling. Shoujin Sun et al. [86] contemplated the impact of cryogenic compacted air cooling during machining of Ti–6Al–4V utilizing carbide inserts. The use of cryogenically compressed air produced better tool life than dry machining. At high cutting speed, occurrence of severe plastic deformation is suppressed. Also applied cooling system was successful in providing low temperature near cutting zone and lessening the chip tool contact length. S. Sartori et al. in another study [44] looked at wear mechanisms of coated and uncoated carbide inserts during machining of Ti-6Al-4V using LN_2 and cooled N_2. In case of uncoated inserts, use of cryogenic coolants excessively cooled the work and hence increased abrasion wear. Nevertheless percentage reduction in flank wear using gaseous N_2, when compared to dry and wet condition was about 55 and 41%, respectively, but decreased to 10% when using LN_2. A parallel result was seen in case of coated inserts also, as cryogenic coolant caused embrittlement of the material. In [2] they have explained that gradual tool wear appears in two forms namely crater wear and flank wear. Flank wear mainly decides life of the tool. The flank wear under conventional and cryogenic conditions during machining of tantalum using tungsten carbide was observed to be 0.57mm and 0.167mm separately. Compared to conventional cooling system, an improvement by 70% was seen in cryogenic cooling.

Sravan Kumar Josyula et. al. [13] contemplated the performance enhancement of liquid nitrogen aided cooling during machining of Al-TiCp metal matrix composites using coated carbide tool. Liquid nitrogen adequately diffused at a low flow rate (10–12 l/h) and at a high velocity (8–50 m/s) in the form of droplet jet over the tool face. The adequately directed atomized liquid nitrogen successfully reduced the tool wear by an amount of 78.71, 56.69, and 37.13%, when compared to dry, wet and cryogenically chilled argon (CCA) gas, individually. Under various machining conditions, 0.8 mm nose radius, 10° rake angle, and 90° approach angle inserts had lower flank wear and surface roughness values, i.e., 22.12 µm and 0.25 µm, respectively. Sunil Magadum et al. [16] evaluated tool life in cryogenic machining of En24 hardened steel (45HRC) using coated carbide inserts. Tests were conducted at 125, 160 and

200 m/min and feed rate and depth of cut were kept constant at 0.1mm/rev and 1mm respectively. From the analyses, it was discovered that utilization of cryogenic coolant yielded best tool life in contrast to use of regular coolant. The improvement in the tool life was 22.46%, 35.74% and 38.60% at cutting speed of 125, 160 and 200 m/min respectively. Shane Y. Hong et al. [20] studied the machining of AISI 304 austenitic stainless steel under cryogenic conditions. In the experiments, liquid nitrogen at 290psi was delivered at the tool chip interface only, avoiding work-tool interface. This methodology brought about 67 % tool life improvement at 3.82 m/s and a 43% improvement at medium speed of 3.40 m/s, when contrasted with regular cooling.

In another study, H13A tungsten carbide inserts was deep cryogenically treated during machining of AISI 1045 steel. They reported a mean reduction in flank wear of 6 %, when machining at 95 m/min. Cryogenically treated carbide inserts endured less pull-out and separation of carbide grains, bringing about a smoother worn zone. However better adhesion between steel and carbide insert resulted in bigger BUE, which shielded inserts from abrasive wear, but increased the stress they were subjected to [43]. Chetan et al. [17] evaluated the performance of deep cryogenic processed carbide inserts during dry turning of Nimonic 90 aerospace grade alloy, using coated and uncoated carbide inserts. The experimental results revealed that cryogenic treatment expanded the hardness of tool because of formation of eta carbide particles and grain refinement process. Little amount of coating failure on the coated inserts was observed under cryogenic treatment. They were found to be better under cryogenic treatment due to low friction (15%), lesser cutting forces (17%) and lesser notch wear formation. A. Iturbe et al. [19] evaluated the surface integrity and tool wear during machining of Inconel 718 with conventional and cryogenic cooling using coated carbide inserts. The test results demonstrated that cryogenic with MQL machining improved the machinability for short machining duration. However longer machining with industrial cutting conditions showed that cryogenic + MQL is not recommendable. The deeper hardened layer due to cryogenic treatment improved the tool life and there by surface roughness. Kejia Zhuang et al [41] studied plasma preheating followed by cryogenic cooling assisted machining of Inconel 718 utilizing ceramic cutting inserts. The plasma nozzle was utilized before the cutting zone to soften the work and liquid nitrogen was situated in the cutting area to remove the generated heat during machining. It was reported that plasma preheating cutting and cryogenic cooled machining had positive impact on the surface roughness and tool life. The surface roughness diminished by 50 % and tool life was stretched out up to more than 40 % over regular machining.

Yogesh V. Deshpande et al [60] examined and reported that cryogenic coolant assisted MQL effectively reduced the tool wear in machining of Inconel 718 using uncoated carbide inserts. MQL removes heat from cutting region and cryo treatment upgraded wear resistance. There was an improvement of 44, 39 and 32% in tool life contrasted withdry for cryogenic, MQL and MQL with cryogenic.

6. Effect of Cryogenic Cooling on Chip Morphology

Chips coming out of machining process contain information related to cutting temperature, hardness etc. [71]. Chip morphology mainly depends upon property of work material and the machining conditions, which includes the cooling effect of coolants [52]. D. Biermann [59] reported about the importance of chip breakability, kinetic energy of the provided cooling medium and the chip formation in machining process. They reported that CO_2-cooling and MQL improved the erosion condition between the chip and the cutting face and affected smaller shear bands between the chip segments, thus chip breaking could be accomplished successfully. In [62], it was said that for a steady feed, the expansion in chip thickness prompted increment in power utilization of machine tool. They conducted turning experiments on Ni–Cr–Co based super alloy under various cooling conditions namely dry, cryogenically cooled tool, MQL and use of cryogenic coolant during machining. The obtained values of chip thickness found to be same for dry and cryogenically treated tool, where as it was low for MQL and cryogenic assisted cooling. The main reasons for above variation were extensive cooling, which produced chips that were smooth and without any side flow. Yusuf Kaynak [73] compared the machinability of Inconel 718 under dry, MQL and cryogenic conditions. They revealed that choosing cutting parameters and cooling/lubricating conditions did not improve chip breakability, however increased cutting speed diminished helical chip diameter. Under cryogenic conditions, thicker chip was obtained, and it was segmented and had bigger pitch than chips generated in dry and MQL conditions. Also it was recommended to machine Inconel 718 at high speeds to obtain good machining outcomes.

Yusuf Kaynak et al. [74] made another examination about the machinability of Ti 5553 under dry, high pressure coolant (HPC), MQL and cryogenic conditions. It was seen that HPC and cryogenic cooling reduced tool–chip contact length,when compared with dry and MQL conditions and chip breakability of Ti-5553 alloy was poor, and among all conditions, only HPC helped to improve chip breaking. Sabrine Trabelsi et al. [83] examined the formation of chip during machining of Ti17 under LN_2 assisted cooling. It was noted that chip was continuous and spiral for a feed rate of 0.1 mm/rev and as the feed increased to 0.3 mm/rev, chip became fragmented. Also cryogenic assistance did not change the colour of chip, whereas it was dark under conventional lubrication. The cryogenic assisted cooling diminished the thermal softening and expanded the flow stress compared to ordinary lubrication.

Ampara Aramcharoen et al. [103] analysed the chip formation during machining of titanium alloy under the influence of cryogenic cooling. They observed formation of helical chips under cryogenic cooling, where as it was snarled chips under oil based cooling system. The reason for this may be delivery of cryogenic coolant on the tool rake face, which isolated and lifted the chip up from the rake surface.In addition, larger tool-chip contact length and radius of chip curvature was observed for oil-based coolant. The negative temperature because of cryogenic cooling decreased thermal effects between tool-chip interfaces and consequently the tool wear rate. Haisheng Lin et al. [76] compared the different cooling techniques such as internal oils on water (IOoW), external oils on water (EOoW) and cryogenic air mixed with MQL (CAMQL) in turning of Ti-6Al-4V alloy. The exploratory outcomes uncovered that chip morphologies created by CAMQL and wet cutting were long constant winding chips, however dry-cut chips formed were tangled spirals. It was concluded that CAMQL cooling has little impact on chip morphology compared with wet cutting. B. Dilip Jerold et al. [78] contemplated the chip morphology during machining of AISI 316 Stainless Steel under CO_2 assisted cooling. They reported that high pressure CO_2 jet helped the chips to break easily and to make tracks in an opposite direction from the cutting zone as chip changed into brittle nature on effective decrease in the cutting temperature at the cutting zone. The washer type chips curly in nature were obtained with the increased thickness at high feed rate. At high cutting velocity, thinner chips with better chip breakability i.e. discontinuous chips was obtained. In case of cryogenic machining of elastomers, M. Putz et al. [22] proposed that there was a huge contrast between chips gotten by dry and cryogenic machining. Cryogenic machining resulted in segmented and partly continuous chips, however in case of dry machining endless ribbon-chips occurred. Likewise chip development was not affected by feed rate and rake edge. In any case, the cooling of elastomers improved the chip development, since material became inclined to brittle fracture.

7. Effect of Cryogenic Cooling on Microstructure and Hardness

Machining process may initiate microstructural modifications on recently machined surface, which can be found as white layers normally during machining of hard-to-cut materials, for example, solidified steels, super-composites, and titanium compounds [53]. The term ‘white layer’ refers to hard layer formation because of phase changes under different cutting conditions, the layer when observed through microscope looks white and hence the name. These white layers regularly contain fine grained martensitic or austenitic structures. The main three expected mechanisms for the formation of white layers are [104, 106]:

- Reaction of surface with environment
- Severe plastic deformation because of high strain, strain rate and temperature.
- Phase transformations because of rapid heating and quenching.

The cutting temperature at the tool, work and chip interface predominantly influence the physical condition of the machined surface. The surface modifications, such as plastic deformation, oxidation, thermal residual stress and metallurgical structural transformations are because of the thermal and/or mechanical loading during the machining process [47]. Domenico Umbrello [56] explored the development of white layer during turning AISI 52100 steel under cryogenic condition utilizing cubic boron nitride inserts. They concluded that utilization of cryogenic coolant constrains the development of white layer, since cryogenic condition somewhat lessens or thoroughly dispenses with the microstructural changes because of quick warming and extinguishing. The same author in another study [61] found that thermal impact was the significant reason for white layer formation in dry machining. [66] Developed a FEM model to comprehend the formation of white layer. The developed model showed that higher cutting temperatures and lower strains were responsible for white layer formation under dry machining. So they determined that during dry machining, white layer formation is mainly because of thermal loading, whereas in case of cryogenic machining, white layer formation mechanism was mainly influenced by mechanically assisted load.

Welber Vasconcelos Leadebal Jr et al. [75] studied the effect of cryogenic cooling on the surface integrity in hard turning of AISI D6 steel utilizing cubic boron nitride tool. In the study liquid nitrogen was passed in three unique ways, on the tool rake face, flank face and both rake and flank face with dry cutting as reference. After turning as per their expectations, hardness of the machined surface increased, an increase of around 8% for the conditions of flank side cooling and rake side cooling and 19% for the condition both rake and flank face cooling were obtained. It was recognized that material on the surface was deformed in the direction of cutting and downwards due to the mechanical load, causing the alignment of the tempered martensitic structure. They were not able to gauge the thickness of the disfigured layer, as no obvious outskirt between these layers and the mass material were found. Palanisamy et al. [79] reported from their experimental work that, as speed, feed and depth of cut increased, micro hardness of work decreased linearly. At lower cutting speed hardness is more, which implied the time taken to shear off material is additionally more. Iturbe et al. [19] examined the micro hardness profiles during machining Inconel 718 under liquid nitrogen (LN) assisted with MQL. They summarized the results as, the micro hardness values observed was high under LN assisted with MQL cooling system and the hardness was increasing with machining time. The hardened layer thickness was matching with the value of depth of cut of 0.2mm. Because of deeper hardened layer, tool life was reduced under LN assisted with MQL compared to conventional cooling.

8. Conclusions

This review paper presents the notable findings of research work did in the territory of utilization of cryogenics for machining processes. Cryogenic cooling is broadly utilized in a wide range of machining forms for machining all classes of materials, especially hard to-machine materials. These materials have unique characteristics, which make their machining difficult and cause problems like excessive tool wear, temperature, strain hardening, hardened surface, poor surface finish etc. Researchers have covered all the important aspects of machining to understand the influence of cryogenics on these and include surface finish, which is the most important requirement of any machining process, followed by tool wear, chip characteristics, microstructure and hardness. Some of the salient findings can be summarized as follows:

1. Cryogenically treated inserts had higher hot hardness. Cryogenic treatment reduces tool wear.
2. Titanium and nickel-based alloys are the most researched difficult-to-machine materials.
3. Use of cryogenic and hybrid cooling strategies improves the surface finish significantly, while machining difficult-to-machine materials.
4. The impact of cryogenic cooling and lubrication is complex, as it is dependent on the interaction of several factors like cutting conditions, cutting insert used and workpiece used and other factors like machine tool etc.
5. Most of the analysts have announced a noteworthy decrease in tool wear during use of cryogenic cooling. The position and direction of coolant feeding affected tool life significantly. Hybrid cooling strategies have also resulted in good surface finish, reduced tool wear etc.
6. Lesser Built-up Edge (BUE) was formed. The magnitude of crater and flank wear, if formed during cryogenic machining was considerably less. However, use of excessive cooling for inserts increased the tool wear.
7. Chip breaking was effective. The chip thickness was higher and it had higher pitch. In machining materials like elastomers, chip formation improved.
8. The formation of white layer was minimized and also the microstructural changes were minimal, while using cryogenics.
9. There was increase in micro hardness of the machined surface and it was seen to be higher for lower cutting speed, feed and depth of cut.

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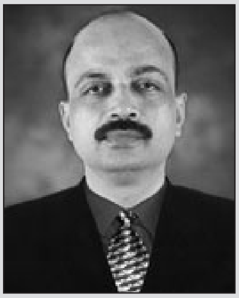

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