



Citation for published version:

Shokrani, A, Dhokia, V, Munoz-Escalona, P & Newman, S 2013, 'State-of-the-art cryogenic machining and processing', *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 7, pp. 616-648.
<https://doi.org/10.1080/0951192X.2012.749531>

DOI:

[10.1080/0951192X.2012.749531](https://doi.org/10.1080/0951192X.2012.749531)

Publication date:

2013

Document Version

Peer reviewed version

[Link to publication](#)

This is an Author's Accepted Manuscript of an article published in Shokrani, A., Dhokia, V., Munoz-Escalona, P., & Newman, S. (2013). State-of-the-art cryogenic machining and processing. *International Journal of Computer Integrated Manufacturing*, copyright Taylor & Francis, available online at:
<http://www.tandfonline.com/doi/abs/10.1080/0951192X.2012.749531>

University of Bath

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

State-of-the-art cryogenic machining and processing

A. Shokrani¹, V. Dhokia¹, P. Muñoz-Escalona², S.T. Newman¹

¹*Department of Mechanical Engineering, University of Bath, Bath, United Kingdom*

²*Department of Mechanical Engineering, Simón Bolívar University, Caracas, Venezuela*

Correspondent author: Alborz Shokrani, Email: a.shokrani@bath.ac.uk, Tel: +44-(0)1225-384049, Address: Department of Mechanical Engineering, University of Bath, Claverton Down, Bath, BA2 7AY, United Kingdom

Abstract

This paper is a state-of-the-art review of the use of cryogenic cooling using liquefied gases in machining. The review is classified into two major categories namely, cryogenic processing and cryogenic machining. In cryogenic processing also known as cryo-processing the cutting tool material is subjected to cryogenic temperatures as a part of its heat treatment process. The majority of the reported studies identify that cryo-processing can considerably increase cutting tool life especially for high speed steel tools. It also identified that in cryogenic machining a cryogen is used as a cooling substance during cutting operations. The cryogen can be used to freeze the workpiece material and/or cutting tool. The paper concludes that cryogenic cooling has demonstrated significant improvements in machinability by changing the material properties of the cutting tool and/or workpiece material at the cutting zone, altering the coefficient of friction and reducing the cutting temperature.

Keywords: cryogenic machining; cryogenic processing; cryogenic cooling; machinability

1 Introduction:

Generally the term cryogenics refers to the science of very low temperatures. Though, this is not specifically defined and can be referred to the temperatures lower than 120°K, the boiling point of air (Timmerhaus and Reed 2007) or 100°K (Karassik et al. 2008). Typical cryogens are usually in the form of liquid gases and can be defined as liquid nitrogen (LN₂), oxygen, helium (LHe), methane, ethane and argon. However, in machining, sometimes temperatures higher than 100°K are also considered by some authors as cryogenics e.g. cryogenic machining using liquid and/or solid carbon dioxide (Abele and Schramm 2008, De Chiffre et al. 2007, Machai and Biermann 2011) and even chilled air at temperatures below (Tsai and Hocheng 1998, Yalcin et al. 2009).

The efforts on liquefying permanent gases goes back to the mid-18th century and the development of the first two thermodynamic laws, followed by liquefaction of oxygen (1877), nitrogen, hydrogen and finally helium in 1908 (Kalia 2009, Timmerhaus and Reed 2007, Dhokia 2009). The word “cryogenic” was first used by Heike Kamerlingh Onnes in 1894 as an adjective in the title of his paper “On the cryogenic laboratory at Leiden and on the production of very low temperatures” (Timmerhaus and Reed 2007).

The early industrial usage of cryogenic technology was limited to the use of liquid oxygen particularly in oxygen-acetylene welding and oxygen furnaces for steel production. The first usage of liquid oxygen for rockets fuels was reported in 1926 in combination with gasoline, followed by the development of alcohol-oxygen fuelled German V-2 rocket during Second World War (Timmerhaus and Reed 2007, Edwards 2003). The studies continued in the United States which led to the development of the Redstone rocket which was first launched in 1953. The successful launch of liquid parahydrogen-oxygen fuelled rockets and the development of thermonuclear bomb and further expansions of the space programmes in the

United States led to rapid growth in gas liquefaction industries in the 1950's (Timmerhaus and Reed 2007).

The application of cryogenic cooling in machining can be categorised into cryogenic processing of the cutting tools and cryogenic machining. The earliest use of a cryogen as a cutting fluid is reported by Reitz in 1919 that used carbon dioxide as a coolant in cutting operations (Shaw and Smith 1956). In cryogenic machining the cryogen medium is introduced into the cutting operation as a coolant in order to change the material properties and/or dissipate the heat generated at the cutting zone (Shokrani et al. 2012b). Cryogenic processing also known as cryo-processing is an extended heat treatment process in a heat treatment cycle and has been acknowledged since 1937 as enhancing tool material properties (Dasilva et al. 2006). In this paper these two categories of cryogenic manufacturing are reviewed and discussed. In addition, the cryogenic machining technique is studied from different points of view, namely machinability and workpiece material.

2 Cryogenic Processing of Cutting Tools:

Cryogenic processing is defined as an extended quench process in the conventional heat treatment cycle. The advantages of cold processing have been known for centuries (Busch 1969). In order to age and improve the stability and wear resistance of watch parts, Swiss watch makers would leave components in cold climates of the Alps for months (Kamody 1999, Busch 1969). While cryogenic processing can improve the properties and specially the wear resistance of all materials which contain retained austenite at the room temperature, (Sreeramareddy et al. 2009) the focus of the current paper is on the cutting tool materials used in machining operations.

2.1 Steel-based Cutting Tools:

The first application of cryogenic treatment on the tool materials is reported by Gulyaev (1937) which exposed high speed steel (HSS) cutting tool to the -80°C to -100°C temperatures for 30 to 60 minutes.

Retained austenite is a soft and ductile allotrope of iron which is unstable at room temperature. Under particular circumstances such as high temperature and pressure during cutting operation, it is likely to transform into martensite which can result in the propagation of micro-cracks. Existence of retained austenite in the cutting tools can result in the rapid tool wear and chipping on the cutting edge (Harris 1970). Traditional quenching converts the majority of the austenite into martensite, though some percentage of the austenite will be retained in the material structure. This is attributed to the fact that the final martensite transformation temperature of eutectoid steel is -50°C , while traditional quenching is limited to the room temperature (Dasilva et al. 2006).

A typical cryogenic process in a traditional heat treatment cycle is as follows:

- (1) Slow cooling to the LN_2 or LHe temperature
- (2) Soaking in the LN_2 or LHe for a reasonable time
- (3) Slow heating to the room temperature

This shows a general cryogenic cycle which is usually executed just after conventional quench processes. However, a single process or even heat treatment cycle cannot be recommended for all tool materials. Each cutting tool should be studied separately based on the cutting process requirements for hardness, toughness and wear resistance of the cutting tool (Gill et al. 2009). The cooling and heating rate to and from cryogenic temperature is particularly important as it can result in thermal shock, material deformation and propagation of micro-cracks. It is evident that some changes happen in the material properties when it is

cooling down (ramp down) and when heated to the room temperature (ramp up) (Kalia 2009). The cooling rate is defined as the third most significant parameter affecting the mechanical properties of steels. In addition to the cooling/heating rate the soaking time is another important parameter of the cryogenic treatment. This is due to the slower atomic movements at very low temperatures. Generally the entire cryogenic process including ramp down and ramp up takes approximately 36 to 72 hours depending on the work material and weight (Kalia 2009).

Dasilva et al. (2006) reported that cryogenic treatment did not affect the hardness, micro-hardness and wear resistance of HSS tool materials, but reduced the wear resistance of TiN coated HSS milling tools. Though, cryogenic treatment increased the HSS drill tool life from 65% to 343% until catastrophic fracture. Ramji et al. (2010) cryogenically treated HSS drill bits and monitored the thrust force and torque as indicators of the tool wear in machining grey cast iron. They found that cryogenic treatment is an effective method to increase the wear resistance of the cutting tool and enhance the surface quality of the holes. Similar results have been reported by Firouzdor et al. (2008) in dry drilling of carbon steel. They reported that cryogenic processing can improve the HSS tool life by up to 126%. In addition, they studied the effect of tempering after the cryogenic process and revealed that it has the potential to improve tool life by 49% as compared to the non-tempered cryogenically treated tools (Firouzdor et al. 2008). Leskovsek et al. (2006) studied the effect of tempering temperature and cryogenic treatment on the M2 HSS tool wear resistance and reported that generally cryogenic treatment improves the HSS tool wear resistance. It should be noted that in this study tempering temperature also affected the wear resistance of the tools significantly. The lowest tool wear was reported for the tools tempered at 600°C regardless of cryogenic treatment. Among the tools tempered at 600°C, the cryogenically treated tool performed slightly better than its counterpart which was only tempered. Molinari et al. (2001)

studied the effect of different cryogenic treatment cycles (table 1) on the wear resistance of M2 HSS tool material. As shown in table 1, in contrast to the results obtained by Firouszor et al. (2008) and Leskovsek et al. (2006) the specimen which was not tempered after cryogenic treatment (B) showed the highest wear resistance. The researchers attributed the improvements to an increase in the material hardness due to cryogenic treatment and concluded that the highest improvements could be achieved if cryogenic treatments were carried out on the quenched and tempered steel (Molinari et al. 2001).

Table 1, Cryogenic treatment cycle and wear rate of M2 HSS tool material (Molinari et al., 2001)

Specimen	Treatment	Wear rate (g/m × 10 ⁻⁶)
A	Quench+Temper+Temper	3.7
B	Quench+Temper+Temper+Cryogenic	1.8
C	Quench+Cryogenic+Temper	2.2
D	Quech+Cryogenic+Temper+Temper	2.4

2.2 Tungsten Carbide Tools

Compared to tool steel materials, there is a very limited number of investigations on the effects of cryogenic treatment on the performance of tungsten carbide tools. Seah et al. (2003) performed a series of experiments in order to investigate the effect of cold and cryogenic treatments on the performance of uncoated tungsten carbide inserts in single point turning of ASSAB 760 carbon steel. They reported that at different cutting speeds, the cold and cryogenically treated inserts have shown more wear resistance than their untreated and quenched counterparts. In addition, it has been found that cold and cryogenic treatment have significantly improved the resistance of the cutting inserts to chipping which was more significant at higher cutting speeds. In another study, Young et al. (2006) cooled a set of uncoated WC inserts at a rate of 0.28°C/min (0.5°F/min) to -184.5°C (-300°F) where the inserts were kept for 24 hours and then heated to the room temperature at a rate of

0.28°C/min (0.5°F/min). Their experimentation consisted of a series of face milling operations at different cutting speeds where other machining parameters were kept constant using cryo-processed and non-treated inserts. They found that while generally cryo-processed inserts performed better than their non-treated counterparts, the effect of cryogenic treatment on the tool life was more significant in wet machining as opposed to dry machining.

Sreemareddy et al. (2009) investigated the effect of cryo-processing on the performance of multi-layer coated WC inserts in turning operations by studying tool wear, cutting forces and surface finish of the machined parts. They reported that cryo-processing significantly reduced the flank wear of the inserts as compared to non-treated inserts resulting in lower cutting forces and surface roughness.

These studies suggest that cryogenic treatment of carbide tools has the potential to improve the productivity and quality through improved wear resistance and surface finish. Despite these achievements, the number of studies in this area is very limited and further investigations on the performance and micro-structure of the cryo-treated WC tools is inevitable.

2.3 Improvement Theories of Cryogenic Processing:

While cryogenic treatment is widely acknowledged by researchers as a technique to improve wear resistance and hardness of cutting tool materials, the underlying reason for these improvements are still unclear. There are several theories to explain the enhancement of the tool materials subjected to cryogenic processing, although none of them can completely explain the reason (Gill et al. 2010).

2.3.1 Austenite Transformation:

The first theory to explain the improvements in cutting tools subjected to the cryogenic treatment is the transformation of retained austenite in the material structure into the harder

martensite allotrope (Preciado et al. 2006). It has been confirmed by X-ray diffraction that cryogenic treatment transforms almost all retained austenite into the martensite. It has been reported (Dasilva et al. 2006, Leskovsek et al. 2006) that the volume fraction of retained austenite in HSS material reduced from almost 25% to nearly 0% by cryogenic treatment. On the contrary, Molinari et al. (2001) compared the retained austenite percentage of two specimens (A and B in table 1) subjected to different heat treatment cycles. X-ray diffraction analysis revealed that both samples contain lower than 2% retained austenite while sample B was harder and more wear resistant. Therefore, in this case transformation of residual austenite cannot explain the enhancements in the material properties of M2 tool steel.

2.3.2 Carbide precipitation and refinement:

Another theory is that cryogenic treatment enhances the precipitation of carbide particles into the martensite matrix. This also results in lower internal stress in the treated material. In addition, it has been reported that cryogenic treatment refines the carbide particles and produces a more homogeneous carbide distribution in the material structure which may result in improved tool life (Firouzdor et al. 2008, Dasilva et al. 2006). Das et al. (2007) classified the carbide particles in the material into primary carbides (PC), large secondary carbides (LSC) and small secondary carbides (SSC). They found that the amount of LSC is significantly lower in cryogenically treated (Quench-Cryogenic-Temper (QCT)) samples than conventionally treated (Quench-Temper (QT)) samples (figure 1). In addition, as it is shown in figure 1, SSCs in the QCT samples were more uniformly distributed and finer. Furthermore, Energy-Dispersive X-ray (EDX) spectroscopy showed that cryogenic treatment produces secondary carbides which are richer in alloying elements.

Moreover the chemical composition of LSC and SSC in the QCT samples was found to be similar, while in QT samples LSCs were richer in alloying elements as compared to SSCs.

It should be noted that generally these mechanisms (carbide precipitation and refinement) require further tempering after the cryogenic treatment to be performed and cannot explain the improvements in the non-tempered cryogenically treated materials as discussed by (Molinari et al. 2001).

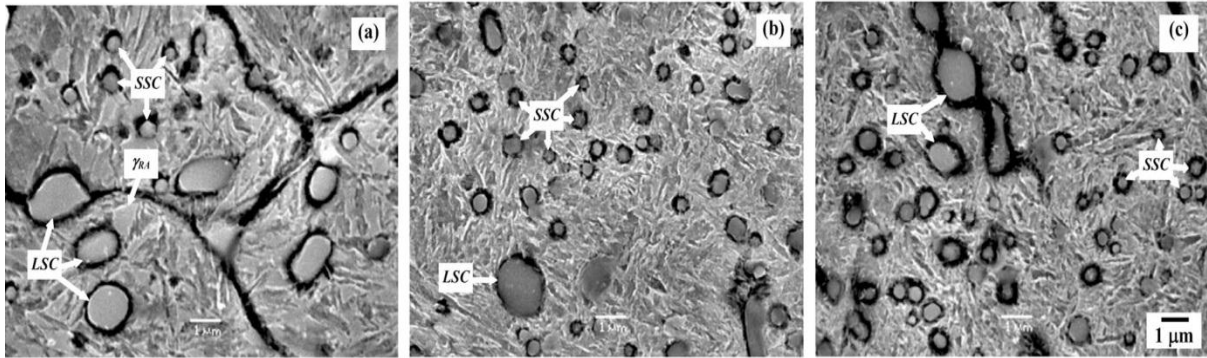


Figure 1, SEM images of microstructure of a) Quenched and tempered, b) quenched, cryo-treated for 36hrs and tempered, c) quenched, cryo-treated for 84hrs and tempered (Das et al. 2007).

2.3.3 Formation of μ phase in the material microstructure:

Unlike ferrous materials, no martensite phase exists in tungsten carbide tools, therefore another mechanism should explain any improvements (Yong et al. 2006). Stewart (2004) attributed the improvements to the change in the formation of cobalt binders as tungsten carbide crystal is a stable structure in the carbide tools. This could explain the tool life improvement by enhancement in the cobalt binder micro-structure where more cobalt binder is retained during the machining operation. Seah et al. (2003) classified the microstructure of tungsten carbide tools into four categories namely:

- α phase: tungsten carbide particles
- β phase: cobalt binders

- μ phase: multiple carbides of tungsten and at least one other binder metal (e.g. Ti, Fe, etc.)
- γ phase: carbide of cubic lattice

Electron microscopy of the microstructure of the material revealed that the cryogenic treatment does not affect α and β phases of the material. Investigations between treated and non-treated specimens revealed that no μ phase existed in non-treated tools while the μ phase appeared after the material was subjected to the cryogenic process. Consequently, changes in the material properties could be attributed to the formation of μ phase in the material microstructure. The presence of μ phase in the material is known to decrease the fracture toughness. On the contrary, as μ phase is harder than the rest of the material, it enhances the wear resistance of the cutting tool. Therefore, the growth of μ phase through the material should be controlled so as to reach the optimum hardness while not affecting the fracture toughness (Seah et al. 2003). Despite the fact that cryogenic processing can change the material properties of cutting tools, there is not any solid evidence to explain the changes in material properties subjected to cryogenic temperatures (Gill et al. 2009).

3 Cryogenic Machining:

Cryogenic machining is a term to describe the use of super cold liquefied gases as coolant in material cutting operations. The aim of this section is to review the effects of cryogenic cooling on the material behaviour during machining and on machinability parameters such as tool life, cutting temperature, surface integrity, etc.

3.1 Material Behaviours at Cryogenic Temperatures:

It has been known that a large proportion of the power consumed for material cutting transforms into heat at the cutting zone (Trent and Wright 2000). This is particularly

important in machining difficult-to-cut heat resistant materials such as nickel and titanium alloys, where the thermal conductivity of the workpiece material is very low resulting in very high temperatures at the cutting zone (Hong et al. 1993, Kitagawa et al. 1997, Arunachalam and Mannan 2000). High temperatures at the cutting zone can affect the tool life, surface finish and geometrical accuracy of the machined part. One approach to dissipate the heat generated during machining is through cryogenic cooling. Cooling the cutting zone by using a cryogen not only cools the cutting zone but could also change the workpiece/cutting tool material properties. Generally, the hardness, modulus of elasticity and strength of materials increase at the cryogenic temperatures. Nevertheless, the effect of cryogenic temperatures on the physical properties, fracture toughness and ductility is not consistent for all materials (Zhao and Hong 1992). Therefore, the study of material behaviour at cryogenic temperatures is an important parameter for defining the suitable cooling approach for machining.

The effect of cryogenic temperatures on the material properties of some materials have been studied by Zhao and Hong (1992) and Hong and Zhao (1999) in order to identify the most appropriate cryogenic cooling techniques. Their studies are summarised as follows:

Soft, low strength, ductile materials such as low carbon steels are usually considered difficult-to-machine due to their welding tendency and difficulties in chip formation. Low carbon steels have a unique ductility to brittleness temperature similar to the glass transition temperature in polymers. At temperatures lower than this temperature, ductility and toughness of the material reduces significantly which favours the machinability. In addition, cryogenic temperatures reduce the welding tendency of the material and reduce the formation of Built Up Edge (BUE). An increase in brittleness not only enhances the chip breakability but also reduces the cutting forces. Hence, it could be concluded that cryogenic cooling of the workpiece is the favourable cooling technique to enhance machinability (Hong and Zhao 1999). A similar mechanism could be expected for polymer materials. Polymers have a

distinctive glass transition temperature in which the polymers transform into a glassy state at the temperatures below it (Kakinuma et al. 2008). This is attributed to the high thermal dependant material properties of polymeric materials. Reduction in the temperature increases the hardness and Young's modulus of the material drastically (Hübner et al. 1998). Hardness of some polymers at different temperatures is provided in table 2.

Table 2, Hardness of some polymeric materials at room and cryogenic temperatures (Hübner et al. 1998)

Temperature	293°K	77°K
Material	Hardness (MPa)	
PA 101	150	750
PTFE	33	450
UHMW	48	520
HDPE	62	550

Another group of materials which react differently at cryogenic temperatures are high carbon steels. The strength and hardness of these materials increase drastically through the reduction in temperature. The hardness of AISI 52100 steel increases from 19HRc at room temperature to about 33HRc at -196°C. In addition, the material strength increases drastically from ambient to the LN₂ temperature while the reduction in toughness is not noticeable. Thus, it is clear that cooling the workpiece material is not favourable as it increases the material hardness and strength while it does not improve the machinability (Hong and Zhao 1999, Zhao and Hong 1992).

Two other materials which were studied by the researchers are A390 cast aluminium and Ti6Al4V titanium alloy. The hardness of Ti6Al4V increases from 32HRc at ambient temperature to 42HRc at the LN₂ temperature while the material maintains its toughness and ductility to a large extent even at cryogenic temperatures. A390 cast aluminium is brittle in

nature and has low impact strength due to the high silicon content in the material structure. Low toughness and ductility are two favourable characteristics for machining operations, though the presence of hard silicon particles results in poor machinability and abrasive wear. Cryogenic cooling of such materials could worsen machinability by increasing micro-hardness of the material.

Reduction in the temperature reduces the thermal conductivity of most materials including Ti6Al4V and Inconel® 718. This could exacerbate the conductive heat dissipation from the cutting zone at cryogenic temperatures (Marquardt et al. 2002). In addition, lowering the temperature lowers the significant heat capacity of the materials which could result in unpredictable behaviour of the material subjected to cryogenic temperature during the cutting operation.

Based on the stated material behaviours at cryogenic temperatures it is clear that no single approach can be defined for cryogenic machining. Furthermore, it cannot be concluded that cryogenic machining is beneficial for machining all materials.

3.2 Tribological Behaviour of Materials at Cryogenic Temperatures and Lubrication Effects of Liquid Nitrogen:

One of the parameters that affect tool life, cutting forces and surface finish of machined parts is the coefficient of friction (CoF) between the cutting tool and the workpiece material. Two main sliding zones in machining materials can be defined as sliding between the chips and the tool rake face resulting in abrasion and crater wear in the rake face and sliding between the machined surface and flank face leading to abrasive flank wear. In this section the effects of low temperatures on the tribological behaviour of the sliding materials and the lubrication effect of liquid nitrogen are investigated.

3.2.1 Tribological Behaviour of Materials at Cryogenic Temperatures:

Generally, it is expected that cryogenic temperature changes the tribological behaviour of the sliding surfaces by increasing surface hardness and reducing the interface temperature. Though, it is not the case for all sliding pairs and is highly dependent on the sliding pair's coating and substrate materials (Ostrovskaya et al. 2001).

El-Tayeb et al. (2009) developed an apparatus to study the effect of spraying LN₂ into the sliding zone on the CoF between tungsten carbide wheel and two types of titanium pins made of Ti-5Al-4V-0.6Mo-0.4Fe (Ti54) and Ti-6Al-4V (Ti64). It has been found that spraying LN₂ can reduce the CoF between carbide wheel and Ti54 pin up to 35% as compared to dry sliding. However, for the Ti64 and tungsten carbide sliding pair LN₂ spray increased the CoF. This effect has been reported to be more significant at higher load and longer sliding time where spraying LN₂ has resulted in up to a 20% increase in the CoF. As shown in figure 2, Hong (2006) developed an apparatus similar to pin-on-disk to study the effect of different cryogenic cooling techniques on CoF including (i) freezing tool specimen, (ii) freezing workpiece sample disk, (iii) freezing tool specimen and workpiece disk simultaneously, (iv) spraying LN₂ into the sliding zone and (v) freezing the tool specimen and spraying LN₂ into the sliding zone simultaneously. A schematic view of the tests is provided in figure 3.

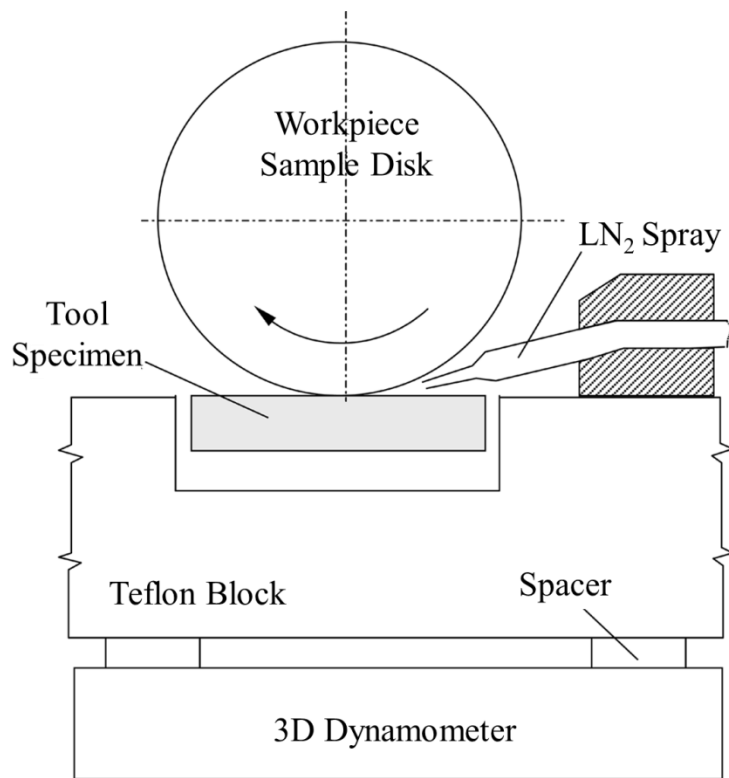


Figure 2, A schematic view of an apparatus similar to pin-on-disk developed by Hong (2006) for studying the tribological behaviour of materials at cryogenic temperatures and lubrication effect of LN₂

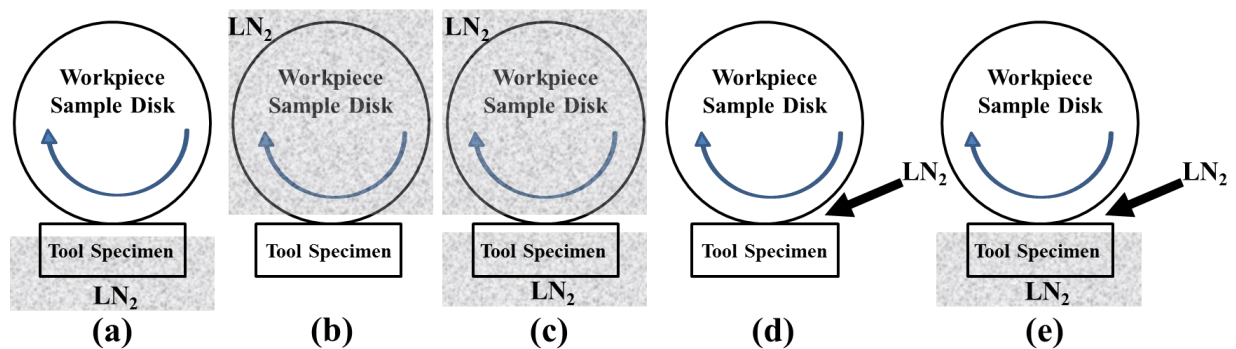


Figure 3, Different cooling techniques studied by Hong (2006) to investigate the lubrication mechanism of LN₂ and tribological behaviour of materials at cryogenic temperatures. (a) Freezing tool specimen; (b) freezing workpiece disk specimen; (c) freezing tool and workpiece Disk specimens simultaneously; (d) spraying LN₂ into the sliding zone and (e) freezing the tool specimen and spraying LN₂ into the sliding zone simultaneously.

In contrary to the previous study by El-Tayeb et al. (2009), Hong (2006) reported that cryogenic cooling of the Ti64 and/or uncoated tungsten carbide sliding pair (concepts i, ii and iii) reduced the CoF significantly. This effect increased when both parts were cooled simultaneously (concept iii). Further studies (Hong 2006, Hong et al. 2002) on the effect of cryogenic temperatures on the tribological behaviour of materials revealed that cryogenic cooling alters the material properties and surface hardness resulting in lower CoF. Nevertheless, this effect is highly dependent on the sliding materials. For instance, cryogenic cooling reduces the CoF between AISI 1018 steel-uncoated tungsten carbide and Ti64-uncoated tungsten carbide pairs while it increases the CoF when AISI 1018 and Ti64 disks are sliding on a CVD (TiN,TiCN,TiC) triple coated carbide tool specimen. This is also the case for an AISI 1018 specimen sliding on a disk of the same material (Hong 2006). Where cryogenically cooled AISI 1018 steel or Ti64 sample is sliding against a solid lubricant CVD triple coated tungsten carbide disk, increases in the load resulted in lower CoF which could be explained by increased temperature at the sliding zone. Higher sliding temperatures could surpass the cooling effect of cryogen media and activate the solid lubricant hence reducing the CoF. Under this condition the sliding nature becomes closer to that of dry sliding at room temperature. The reduction rate of the effective shear strength with the decrease in temperature of some metallic materials is lower than the reduction rate of their yield stress. The CoF of these metals could be altered by reduction in the interfacial temperature by properly applied cryogenic cooling (Hong et al. 2002).

Cryogenic temperature changes the material properties of the polymeric materials such as polytetrafluoroethylene (PTFE) and polyamide 6. Hübner et al. (1998) stated that changes in the polymeric material properties due to cryogenic temperature results in reductions in frictional forces when sliding against a steel disk.

3.2.2 *Lubrication Effects of Liquid Nitrogen:*

In addition to the effects of low temperatures on the tribological behaviour of materials, Hong (2006) also studied the effect of spraying LN₂ between the sliding surfaces using a device similar to pin-on-disk test (figures 2, 3a and 3b). As a result of the studies, the researcher stated that LN₂ forms a lubrication film between the sliding surfaces resulting in lower CoF. He also stated that unlike cryogenic cooling, the lubricating effect of LN₂ is independent on sliding materials and can reduce the CoF effectively. For instance, in the case of sliding against solid lubricant coated carbide where cryogenic cooling increased the CoF, penetrating LN₂ between the sliding surfaces reduces the CoF as compared to dry sliding. In another pin-on-disk set of experimentation, El-Tayeb et al. (2010) also reported that LN₂ forms a boundary film between the sliding surfaces which reduces the wear and CoF. However, Hong et al. (2002) argued that in machining operations, LN₂ cannot provide a boundary lubrication similar to conventional lubricants. LN₂ evaporates quickly at the cutting zone and it is very difficult to keep it between the sliding surfaces. Therefore, the lubrication effect of LN₂ is attributed to the formation of a hydraulic cushion of LN₂ between the sliding surfaces provided by the spraying pressure which carries a portion of normal loads (Hong et al. 2002, Hong et al. 2001a). This could explain the increase in the CoF as a result of increases in the normal load where the LN₂ is squeezed from the contact area or cannot be penetrated into it due to low spraying pressure. Jun (2005) developed three models based on force component projection, geometrical relationship and vector manipulation in order to evaluate the machining forces and calculate the normal and friction forces in turning. The results are then used to specify the CoF at the cutting zone. He used the models to investigate the lubrication effect of LN₂ sprayed on the rake and flank faces of WC cutting insert in machining Ti64 and AISI 1018 steel. Empirical and computational investigations indicated that applying LN₂ significantly reduced the CoF in the machining of steel and titanium materials. It was found

theoretically that spraying LN₂ into the cutting zone could reduce the CoF by 0.3 and 0.4 for Ti64 and AISI 1018 steel respectively. Although in practice, the cooling mechanism reduced the CoF by 0.27 in machining Ti64 and 0.35 for the AISI 1018. In addition, it was found that LN₂ spraying is more effective at high cutting speeds in machining AISI 1018. This is due to increases in the material hardness due to low temperatures at lower speeds which surpasses the lubrication effect of LN₂.

Hong et al. (2002) summarised the effects of spraying LN₂ between the sliding surfaces as:

- Changes in the material properties of sliding pairs;
- Formation of a liquid/gas film between the sliding surfaces reducing the contact area resulting in lower friction forces;
- Reduction in interfacial temperature resulting in the modification of the sliding surfaces by reducing the chemical reactivity and welding tendency;
- Increasing the surface hardness of the sliding materials and reducing the tendency of CoF to be increased over time.

3.3 Cryogenic Cooling Techniques in Machining Operations:

Different techniques have been adopted in order to apply the cooling effect of cryogenic media into the cutting process. These techniques can be classified into workpiece cooling, cutting zone and/or chip cooling and indirect cutting tool cooling (Yildiz and Nalbant 2008) or the combination of these techniques. Though, defining a clear border between these techniques is not applicable due to the complex nature of the cutting process especially in intermittent operations. In addition each technique consists of some subcategories which are further discussed in following sections.

3.3.1 *Cutting Zone Cooling:*

One of the most widely researched methods of using cryogenic coolants is spraying the cooling media into the cutting zone or the tool-chip contact area. Different approaches have been implemented to penetrate the coolant media into the cutting zone. The main objective of this technique is to dissipate the heat generated during the cutting operation, cool down the cutting tool, enhance the cutting tool properties and alter the CoF, while preventing alterations in the workpiece material properties.

Cryogenic cooling of the cutting tool reduces the chemical reactivity of the tool material resulting in lower adhesion and diffusion wear. Bermingham et al. (2011a) reported that while cryogenic cooling is not capable of reducing cutting temperature to a point that prevents diffusion and attrition wears, it significantly reduces the wear rate and extends the tool life. At cryogenic temperatures the cutting tools become harder, thus lower abrasive wear is expected. Lower tool wear means that the cutting edge can literally remain intact for a longer time resulting in improved surface roughness as compared to dry machining.

In order to spray the cryogen into the cutting zone two approaches are common namely: 1) using an external nozzle and 2) modifying the cutting tool or tool holder. As the cryogen cannot be circulated in the machine tool, economical consumption of the cryogen is very important. Hence, the most economical approach is to bring and penetrate it at the exact point where it is required (Hong and Ding 2001a).

Axer (1954) modified a carbide tool by drilling a hole in the flank face of the tool to spray cryogen into the cutting zone. Hong (1999) integrated a chip breaker and a cryogenic nozzle and developed an innovative LN₂ spraying device for turning applications. As shown in figure 4, the device was designed to spray LN₂ on the rake face and/or flank face of the cutting tool. The chip breaker helps to raise the chips and let the LN₂ penetrate into the tool-chip contact area effectively. Experimental investigations (Hong and Ding 2001a) revealed

that the most effective approach is spraying the cryogen simultaneously on both the flank and rake face to cover both flank and crater wear zones. They also found that the effect of cooling the rake face is more significant than the flank face.

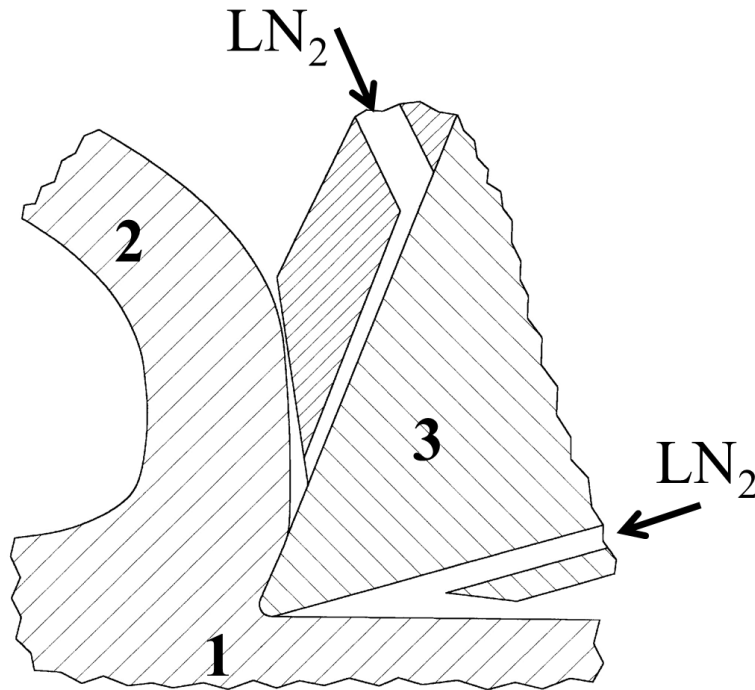


Figure 4, Cryogenic cooling device for turning operations with integrated chip breaker designed and patented by Hong (1999). 1- workpiece, 2- chip, 3- cutting tool.

Birmingham et al. (2011a) noted that in turning of Ti-6Al-4V alloy, spraying LN₂ simultaneously on the rake and flank faces and the nose of the tool yields to the highest tool life improvement as compared to other cooling methods. Dhananchezian and Kumar (2011) modified an ISO K10 CNMG 120408 MP1-KC 5010 carbide insert. Dhar et al. (2002b), Venugopal et al. (2007b, 2007a) and Kenda et al. (2011) used a set of external nozzles to impinge LN₂ along the main and auxiliary cutting edges of carbide inserts. The objective of their nozzles was to cover the rake and flank face of the cutting tool by LN₂ and penetrate the cryogen into the chip-tool contact area. While LN₂ could reach close the cutting zone and

reduce the cutting temperature, it failed to penetrate into the chip-tool contact zone. Machai and Biermann (2011) modified the clamping jaw of the cutting insert and delivered liquid carbon dioxide (LCO_2) to the cutting zone through two holes in the clamping jaw. It has been reported that the CO_2 stream has failed to reach the tool-chip contact area and reduce the chemical affinity of the titanium alloy workpiece.

For milling operations, Nalbant and Yildiz (2011) designed an external jet system to spray LN_2 into the tool-workpiece interface. They reported that the system cooled the cutting tool and the workpiece together and resulted in over hardening of the workpiece material. Biermann and Heilmann (2010) designed two delivery systems for face milling operations in order to reduce burr size in machining aluminium alloy workpiece. The first system was stationary in relation to the workpiece, while the second system consisted of five nozzles placed around the face mill cutting tool and was fixed in accordance to the feed motion of the cutting tool. Experiments illustrated that smaller burrs can be achieved by using the second cooling system.

3.3.2 Workpiece Cooling:

Cryogenic cooling of the workpiece material before or during the cutting operation is one of the most widely used cryogenic machining techniques. The main objective of this technique is to change the material properties of the workpiece in order to enhance machinability. To cool the workpiece two methods are commonly used, namely cryogenic bath and/or cryogenic spray. In cryogenic bath cooling the workpiece is usually submerged in a cryogen, while in workpiece cooling with spray jets the cryogen is sprayed onto the workpiece during machining and just before the cutting operation.

Uehara and Kumagai (1968, 1970) developed two approaches for cooling the workpiece during turning operations. The first concept (Uehara and Kumagai 1968) was to inject LN_2

into the workpiece through a copper tube placed in the main spindle of a lathe machine. The second system (Uehara and Kumagai 1970) consisted of two copper tubes with holes facing the workpiece material acting as spraying nozzles. LN₂ was sprayed through the holes on the workpiece surface before the cutting zone. Ahmed et al. (2007) modified a PSBNR 2525 M12 standard turning tool holder to deliver LN₂ close to the cutting edge. The discharged nitrogen is sprayed onto the chips to increase chips embrittlement. Increased brittleness enhances chip formation for ductile materials which normally produce continuous chips in cutting operations.

Mishima et al. (2010), Kakinuma et al. (2008, 2012) and Dhokia et al. (2010) developed fixturing solutions for freezing elastomer workpieces of different materials and keep their temperature below the glass transition temperature during machining operations. The glass transition temperature is a characteristic of polymer materials where the material transforms into a rigid and stiff glassy state (Kakinuma et al. 2008, Dhokia et al. 2010). This transition allows the material to withstand the cutting forces and make the machining operation possible. Kakinuma et al. (2008) cryogenically cooled a poly-dimethyl-siloxane (PDMS) workpiece using a specially designed fixture which contained LN₂ as a cooling media. They stated that cryogenic machining enhanced the machinability of PDMS drastically, however super cold temperature resulted in geometrical inaccuracies in the machined part. Truesdale and Shin (2009) used a nozzle to spray LN₂ for face milling Udimet 720 nickel based alloy. The nozzle was designed to pre-cool the workpiece just before the cutting operation without affecting the cutting tool.

3.3.3 *Indirect Cooling:*

In this technique the heat generated during machining is dissipated by conduction through the cutting tool. Traditional indirect cooling of the cutting tool also known as heat pipe consists

of three sections namely evaporation, adiabatic and condensation. The heat generated at the cutting zone transforms into the evaporation section by conduction and evaporates the cooling fluid. The vaporised fluid is then transferred to the condensation section through the adiabatic unit. The vapour is then cooled and liquefied in the condensation section (Noorul Haq and Tamizharasan 2005, Jen et al. 2002). In indirect cryogenic cooling of the cutting zone, there is no requirement for the adiabatic and condensation units, as the cryogen media does not require cooling and evaporates to the atmosphere after absorbing the heat.

The cryogen coolant is delivered to a chamber designed over or beneath the cutting tool. The cryogen absorbs the generated heat at the cutting zone through conduction and evaporates. The evaporated cryogen is then released to the atmosphere through the outlet of the chamber. The main objective of this technique is to freeze the cutting tool without direct contact between the cryogen and the cutting zone or workpiece.

Wang et al. (1996) designed a tool cap placed over the cutting tool so as to concentrate LN₂ over the cutting tool's back face. An identical design was used (Wang et al. 2003) for plasma assisted machining of Inconel® 718, while similar method was employed by Dandekar et al. (2010) for hybrid laser assisted turning of Ti6Al4V titanium alloy. The laser beam was used to heat and soften the workpiece material while LN₂ was employed to freeze the cutting tool. Rozzi et al. (2011) designed a heat exchanger for a modified turning tool holder. The heat exchanger was placed under the cutting tool to transfer the heat from cutting tool to the LN₂ inside the heat exchanger. Ahmed et al. (2007) modified a PSBNR 2525 M12 standard turning tool holder to deliver LN₂ beneath the cutting tool. In their system, the LN₂ absorbed heat from cutting tool, evaporated and then released into the atmosphere away from the workpiece so as to prevent cooling of the workpiece resulting in hardening.

In this technique the cryogen is not in direct contact with the workpiece, therefore the negative effects of cooling the workpiece, such as geometrical deviations and increase in material

strength and hardness could be eliminated (Wang and Rajurkar 2000). However, the effectiveness of the technique is highly dependent to the cutting tool material properties.

3.4 Effects of Cryogenic Cooling from Machinability Point of View:

In this section the effect of cryogenic cooling on the cutting forces, cutting temperature, tool life and surface integrity is reviewed.

3.4.1 Effect of Cryogenic Cooling on Cutting Forces:

As clarified in previous sections, the application of cryogenic media in the machining operations can increase the hardness and strength of workpiece/cutting tool materials, change the material toughness, CoF, reduce the chemical reactivity and welding tendency of the workpiece/tool materials etc. The effect of using cryogenic coolant on the cutting forces and power consumption is highly dependent on the tool/workpiece material and cooling technique. Indeed, it cannot generally be concluded that cryogenic cooling can result in reductions or increases in cutting forces.

Aggarwal et al. (2009) studied the cutting parameters of turning operations of AISI P-20 steel using TiN coated tungsten carbide tools in order to optimise the turning cutting forces. They found that the environment is one of the most significant parameters for cutting forces. Despite the 10% increase in the material hardness at the cryogenic temperature, they concluded that the cryogenic environment is desirable in order to achieve the lowest cutting forces (Aggarwal et al. 2009). A similar conclusion was drawn for optimisation of power consumption, where the cryogenic environment was found to be the most significant parameter (Aggarwal et al. 2008b). Spraying LN₂ on the crater and flank faces of uncoated carbide tools has been reported by Paul and Chattopadhyay (2006) showing significant reductions in cutting forces when machining different steels, namely AISI 1040, AISI 1060, AISI E4340C, AISI 4140 and AISI 4320. Similarly it has been stated (Dhar et al. 2002a, Dhar

et al. 2002d) that cryogenic turning resulted in significant reductions in cutting forces in machining AISI 1040 and AISI 4320 steels as compared with dry machining. Jainbajranglal and Chattopadhyay (1984) attributed reductions in cutting forces in machining carbon steel materials to the transformation of chip formation into brittle fracture and reduction in the formation of BUE on the cutting edge.

In contrary to these papers, it has been indicated (Dhananchezian et al. 2009) that the application of LN₂ to the rake face of the cutting tool in machining AISI 1040 and 6061-T6 aluminium increased the cutting forces by 15% and 10% respectively. Hong and Ding (2001b) declared that the application of the cryogen increased the cutting forces by 8% in turning AISI 1008 low carbon steel with an uncoated tungsten carbide tool. This could be attributed to the different cooling techniques used by the researchers. For instance Dhar et al. (2002a) modified a carbide insert in order to inject LN₂ into the cutting zone while the Hong and Ding's (2001b) concept was to cool the rake face together with the chips so as to enhance chip breakability. Jun (2005) experimentally studied the effect of material hardening on the cutting forces in turning AISI 1018 steel. He found that applications of LN₂ at higher speeds could reduce cutting forces, while at lower cutting speeds the lubrication effect is surpassed by an increase in the material hardness. Therefore, the researcher concluded that to obtain the lubrication effect of LN₂ it should be penetrated into the chip-tool interface. It is noteworthy to mention that one of the problems in investigating the lubricating effect from cutting forces is that other affecting parameters, such as material properties of sliding pairs and tool-chip contact area are being neglected. For instance, in this paper the lubrication effect has been attributed to the changes in the material properties and not to the lubrication effect of the LN₂ itself. However, in order to understand the real mechanism of reduction in the CoF, further studies considering other involving parameters are required.

In machining AISI 202 stainless steel it has been reported (Kalyankumar and Choudhury 2008) that spraying LN₂ on the cutting edge reduced the cutting forces by up to 14.83% in comparison with dry machining. Nalbant and Yildiz (2011) used an external nozzle to spray LN₂ into the tool-chip interface in milling AISI 304 stainless steel. They stated that the cryogenic temperature resulted in excessive increases in the workpiece material hardness. Applying LN₂ increased the cutting forces by 6.5%, 5.6% and 3.3% along the X, Y and Z axes respectively. It also increased the spindle torque by 7.9%. In addition, further studies on the effect of cooling the workpiece by LN₂ in turning AISI 304 stainless steel illustrated that cryogenic cooling of the workpiece is not favourable as it leads to drastic increases in material hardness and thus cutting forces (Uehara and Kumagai 1968, Uehara and Kumagai 1970).

Dhananchezian and Kumar (2011) reported that in turning Ti64 with a modified PVD TiAlN coated carbide tool, application of cryogenic coolant on the rake face reduced the main cutting force and feed force by 38% and 39% respectively as compared to wet machining. Bermingham et al. (2011b) studied the effect of cryogenic cooling of the rake and flank faces of a WNMG 120408 MF1 WC carbide tool with an integrated chip breaker in turning Ti64 material. LN₂ was delivered through the tool holder to the rake face and an external nozzle was used to spray LN₂ on to the flank face. Experimental measurements of the cutting forces revealed that this technique reduced the main cutting force and increased the thrust force, whereas this did not change the feed force significantly, regardless of the cutting parameters. Likewise, Ke et al. (2009) stated that the application of cryogenic cooling in high speed milling (HSM) of Ti64 by TiAlN coated carbide tool resulted in 32.7% reduction in the cutting force. It has been attributed to the enhanced chip flow and reduction in BUE and tool wear (Ke et al. 2009). In turning Ti-10V-2Fe-3Al alloy with TiAlN-TiN coated carbide with CNMG 120404 geometry the application of LCO₂ reduced the main cutting and feed forces

while formation of CO₂ snow on the surface resulted in higher radial forces as compared to emulsion cooling (Machai and Biermann 2011). Hong et al. (2001a) studied the effect of different cryogenic cooling concepts on the cutting forces in turning Ti64 workpiece using uncoated WC cutting tools. The cooling concepts were spraying LN₂ on the i) rake face, ii) flank face and iii) rake and flank face simultaneously. The researchers concluded that cryogenic machining regardless of cooling technique increases the thrust and main cutting forces, while reducing the feed force. Experiments showed that spraying LN₂, simultaneously on flank and rake face resulted in the highest increase in cutting forces as compared to the other two techniques. Hence, it was found that extra cooling of the workpiece resulted in increased cutting forces. In addition, the reduction in the feed force was attributed to the lubrication effect of LN₂. However, the conclusion of this study is in contrast with previously stated research in machining Ti64 titanium alloy.

Wang et al. (2002) indirectly cooled a H13 carbide insert with cobalt binders in turning tantalum. They found that up to 60% reduction in cutting forces can be achieved using this technique. Wang et al. (2003) used a similar cryogenic cooling technique for plasma-enhanced hybrid turning of Inconel® 718. A plasma beam was employed in order to heat and soften the workpiece material just before cutting. In addition, a cooling cap was placed on the silicon carbide whisker reinforced alumina ceramic cutting insert so as to cool the cutting tool using LN₂. The technique resulted in a 30%-50% reduction in cutting forces as compared to conventional dry machining. They attributed the enhancements to 1) the lower workpiece material hardness and strength due to plasma heating and 2) increase in the cutting tool material strength and hardness due to cryogenic cooling. In machining Udimet 720 nickel based alloy, Truesdale and Shin (2009) suggested that cryogenic conventional-milling is more favourable than cryogenic down-milling and dry machining as lower cutting forces are produced in this method. Interestingly while cryogenic cooling of the workpiece reduces the

cutting forces in conventional-milling, it yields to higher cutting forces in down-milling as compared to dry machining.

As discussed above, it has been found that the cooling approach and workpiece material are two important phenomena that affect the cutting forces. Similar cooling techniques could yield different results in machining different materials. In addition, different results could be obtained by different cooling techniques in machining similar materials.

3.4.2 Effect of Cryogenic Cooling on Cutting Temperature:

Cutting temperature is an important phenomenon in machining operations, which affect tool life, power consumption, cutting forces, surface finish and geometrical accuracy of machined parts. It is more important in machining difficult-to-machine materials where the thermal conductivity of the workpiece material is very low. The generated heat at the cutting zone cannot be effectively dissipated through the workpiece or chips. This would result in very high localised temperatures at the cutting zone and the tool rake face.

The main application of coolants is to reduce the cutting temperature through conduction. However, at very high cutting temperatures the conventional cutting fluids evaporate before reaching the cutting zone and fail to penetrate into the tool/chip interface. Evaporation of the cutting fluids in contact with hot surfaces results in the formation of a hot vapour cushion at the cutting zone and over the hot surfaces which exacerbates the conduction and further increases the cutting zone temperature (Abele and Fröhlich 2008, Astakhov 2006).

It is known and empirically proved that an increase in the cutting speed increases the cutting temperature (Schulz and Moriwaki 1992, Astakhov 2006). Higher cutting temperatures could soften the workpiece material which together with other phenomena could improve machinability (Wang 2005, Truesdale and Shin 2009, Kalyankumar and Choudhury 2008). Yet, this effect is not limited to the workpiece material and could also soften the cutting tool

material. In addition, it increases the chemical reactivity between the workpiece and cutting tool materials and deteriorates adhesion and formation of BUE. Consequently, it is important to control the temperature at the cutting zone by reducing the heat generation and/or heat dissipation for instance, by proper selection of the cutting parameters (Dhar and Kamruzzaman 2007). This is more important in the case of difficult-to-machine materials, such as titanium and nickel alloys where the workpiece material maintains most of its mechanical properties at elevated temperatures. On the other hand, controlling the cutting temperatures in order to extend the tool life has resulted in very low productivity (Shokrani et al. 2012b).

Using cryogenic media particularly LN₂ as coolant in different machining operations has been reported as an effective method to reduce cutting temperatures (Dhananchezian et al. 2009, Dhar et al. 2002d, Benfredj et al. 2006, Hong and Ding 2001a). Dhar et al. (2002d) investigated the effect of cryogenic cooling in turning steel with WC tools. In order to estimate the cutting zone temperature they simplified the problem to a 2-dimensional model of orthogonal machining. In addition, four boundary conditions were defined as room temperature, constant temperature which was set to the LN₂ temperature around the cutting zone, thermally insulated zone and convective heat transfer boundary zone. Computational FEA was conducted using NISA FEA software (2011) and revealed that the model tends to overestimate the results in comparison with measured values using a tool-work thermocouple with an average of 5.4% deviation. Based on the computational and empirical investigations it has been found that cryogenic machining significantly reduces the tool-chip interface temperature. It is attributed to improved heat conduction, reduction in tool-chip contact length and improved chip breakability as a result of spraying LN₂ into the cutting zone (Dhar et al. 2002d).

In machining aluminium 6061-T6, a reduction in the cutting temperature up to 39% has been reported as a result of spraying LN₂ onto the rake face of an uncoated WC tool (Dhananchezian et al. 2009). Wang et al. (1996) used a thermocouple placed in 2×1mm distance from the cutting edge, while Uehara and Kumagai (1968) employed the tool-chip thermocouple method to measure the cutting zone temperature. While both of them failed to measure the actual cutting temperature, the measured results show the effect of LN₂ cooling on the cutting zone temperature. The researchers (Uehara and Kumagai 1968, Wang et al. 1996) concluded that the application of LN₂ resulted in reduction in the cutting zone temperature.

In end milling hardened AISI H13 die steel Ravi and Kumar (2011) reported that spraying LN₂ into the cutting zone could reduce the cutting temperature by 57%. Hong and Ding (2001a) measured the cutting temperature in turning Ti64 using uncoated WC insert under different cutting environments. They ranked the machining environments in terms of effectiveness (highest cutting temperature to the lowest) as: i) dry cutting; ii) indirect cryogenic cooling; iii) emulsion coolant; iv) cryogenic cooling of flank face; v) cryogenic cooling of rake face and vi) simultaneous cryogenic cooling of flank and rake faces. Ben Fredj et al. (2006), Fredj and Sidhom (2006) and Paul and Chattopadhyay (1996a) reported that injecting LN₂ into the tool-workpiece interface in grinding steels reduced the grinding zone temperature significantly. Fredj and Sidhom (2006) indicated that reductions in the grinding zone temperature resulted in improvements in the fatigue life and surface integrity of the ground AISI 304 stainless steel part.

From the literature (Benfredj et al. 2006, Paul and Chattopadhyay 1996a, Paul and Chattopadhyay 2006, Uehara and Kumagai 1970, Uehara and Kumagai 1968, Ghosh et al. 2003, Wang and Rajurkar 1997, Truesdale and Shin 2009, Dutra Xavier et al. 2011, Ravi and Kumar 2011) it can be found that regardless of cooling technique using LN₂ as cryogen is an

effective method to dissipate and reduce the chip-tool interface temperature which could lead to a reduction in thermally induced tool wear mechanisms.

3.4.3 Effect of Cryogenic Cooling on Tool Life:

It is clear that cryogenic coolant, in particular LN₂ increases tool life by reducing the chemical reactivity of the workpiece material with the cutting tool and also by increasing the cutting tool hardness (Birmingham et al. 2011b). The Taylor equation is one of the well-known equations in tool life prediction.

Taylor Equation: $VT^n = C$

Where V is cutting speed in m/min, T is tool life in min and n and C are machining constants which are related to depth of cut, feed, workpiece and tool material (Taylor 1907)

Based on the Taylor equation, it is clear that the tool life is highly influenced by the cutting speed and thus cutting temperature. Evans and Bryan (1991) indicated that in single point diamond turning of stainless steel graphitisation and dissolution are two dominant tool wear mechanisms. This is mainly attributed to the affinity of carbon to ferrous materials. They reported that by indirect cooling of the cutting tool using LN₂, the tool wear reduced significantly where no wear could be detected at 400X magnification after machining 1000 mm² of 440V steel. On the contrary, machining with the diamond tool was stopped due to excessive wear when machining a similar area in dry environment. Pahlitzsch (1953) reported that using LCO₂ and LN₂ resulted in 150% and 240% respectively longer tool life as compared to dry cutting. He attributed the improvements to the exclusion of the oxygen from the cutting zone as a result of applying inert carbon dioxide or nitrogen.

Ahmed et al. (2007) compared the tool life in dry cutting with two cryogenic cooling techniques. At the cutting speed of 250 m/min, cooling the cutting tool and chips (concept 1) resulted in a 30 times improvement in tool life as compared to dry cutting. By only cooling

the cutting tool and releasing the nitrogen gas away from the cutting zone (concept 2) the tool life increased even further. At the cutting speed of 450m/min the tool in concept 2 performed 13 times longer than concept 1. This was explained by over hardening of the workpiece material in concept 1, where the nitrogen gas was released towards the chips as well as the workpiece.

It has been reported (Hong and Ding 2001a) that simultaneous spraying of LN₂ on the rake and flank faces of the cutting tool can reduce chemical reactivity of Ti64 to the WC cutting tool. The diffusion rate of the workpiece material to the cutting tool could be controlled significantly and resulted in increased tool life. It should be noted that diffusion is one of the dominant wear mechanisms in machining titanium alloys as titanium is chemically reactive to all known tool materials (Hong and Ding 2001a, Paul and Chattopadhyay 2006). Similarly, Klocke et al. (2012) reported that cryogenic cooling using LN₂ or CO₂ has significantly improved the tool life of cemented carbide tools in turning Ti64 material. The researchers attributed the 5 times improvement in tool life when using LN₂ as compared to conventional flood coolant to the improved heat conduction resulting in lower cutting temperatures.

Khan and Ahmed (2008) modified a tool holder to cool the cutting tool through a chamber under the cutting insert and spray a cryogen media onto the cutting edge. By cooling the TiCN coated WC cutting tool using LN₂, a 4 times improvement in comparison with conventional emulsion coolant was achieved in turning AISI 304 stainless steel. AISI 304 stainless steel is particularly interesting as it retains its ductility even at cryogenic temperatures while its hardness increases significantly. Thus, Khan and Ahmed (2008) successfully increased the hardness of the carbide tool, while the workpiece material remained intact. The dominant tool wear mechanism in machining AISI 304 stainless steel with WC tool was abrasion and attrition on the flank face and abrasion and diffusion on the

rake face resulting in crater wear. Cryogenic cooling has been observed to effectively reduce the diffusion and abrasion and increase the tool material hardness.

Hong and Broomer (2000) compared the tool lives in machining AISI 304 stainless steel in different cooling techniques, namely state-of-the-art emulsion coolant through the tool holder, LN₂ flood, cooling the rake face along the Z-axis (rake Z), cooling the rake face along the X and Z axes (rake X and rake Z), cooling the rake face along the Z and X axes together with flank face and rake X and Z axes with LN₂. The experiments showed that the lowest tool wear is achieved by spraying LN₂ along the Z-axis to the rake face. Using this method, up to 67% and 43% increase in tool life could be expected at 3.8m/sec and 3.4m/sec cutting speeds respectively in comparison with emulsion cooling. Indirect cryogenic cooling of the TiAlN coated WC tool in machining AISI 416 stainless steel resulted in a 10 times increase in tool life. The application of LN₂ in turning AISI 202 stainless steel with PVD TiN coated WC tool reduced the flank wear by 37%. This is attributed to the reduction in the cutting zone temperature preventing the tool material from softening (Kalyankumar and Choudhury 2008). Ghosh et al. (2003) declared that spraying two-phase gas/liquid droplets of LN₂ on the rake face of TiN coated WC tool doubled the tool life in machining AISI A2 tool steel as compared to wet machining. Machai and Biermann (2011) reported a two times increase in tool life of (Ti-Al)N-TiN coated WC tool in machining Ti-10V-2Fe-3Al titanium alloy as a result of using LCO₂ at the cutting zone in comparison with conventional emulsion cooling. These improvements are also supported by studies conducted by Venugopal et al. (2007b, 2007a) in cryogenic turning of Ti64 with uncoated WC tool. The studies indicated that cryogenic cooling reduced the tool crater and flank wear by 77% and 66% respectively as compared to dry machining. This resulted in up to a 240% and 71% increased tool life in comparison with dry machining and emulsion cooling respectively.

Bermingham et al. (2011b) stated that by injecting LN₂ on the flank and rake face of WC tools in machining Ti64, a 43% to 58% improvement in the tool life could be achieved although the improvement is lower than in previous studies. They found that the main tool failure mode regardless of cutting environment was crater wear which was confined to the nose or distributed along the rake and nose in high and low feed rates respectively. In dry turning of the AISI 52100 steel the PCBN tool failed prematurely prior to 300µm flank wear due to nose fracture (Ghosh et al. 2003). It has been proven that spraying LN₂ on the rake face during the operation prevents nose fracturing (Ghosh et al. 2003, Dutra Xavier et al. 2011) and resulted in up to a 65 times improvement in tool life by limiting flank wear to 250µm (Dutra Xavier et al. 2011).

In machining Inconel® 718, Kopac (2009) integrated MQL and cryogenic machining by spraying LN₂ on the flank face and an oil-mist onto the rake face. The technique yielded a significant reduction in both crater and flank wear resulting in longer tool life as compared with dry and MQL machining. The dominant tool failure mechanism regardless of cooling technique was crater wear leading to catastrophic tool failure (Kopac 2009). Pusavec et al. (2010) reported that by employing LN₂ cooling in turning Inconel® 718 with TiAlN coated WC tools, machining time could be reduced by up to 63% as a result of the increase in tool wear resistance and thus cutting speed. Longer tool life means that the cutting nose will literally remain intact for a longer time.

3.4.4 Effect of Cryogenic Cooling on Surface Integrity:

Surface integrity is one of the most important parameters in assessing the performance, quality and reliability of a machined part throughout its service life (Ulutan and Ozel 2011, Kenda et al. 2011). It is shown in figure 5 that surface integrity defines the mechanical, metallurgical and topological properties of a machined surface. Residual stress and surface

roughness are two important parameters of surface integrity in machining and considerable research (Ulutan and Ozel 2011, Thiele and Melkote 1999, Pusavec et al. 2011, Zurecki et al. 2003, Paul and Chattopadhyay 1996b, Umbrello et al. 2012) has been conducted on the study of the effect of machining parameters and machining environments on residual stress and surface finish.

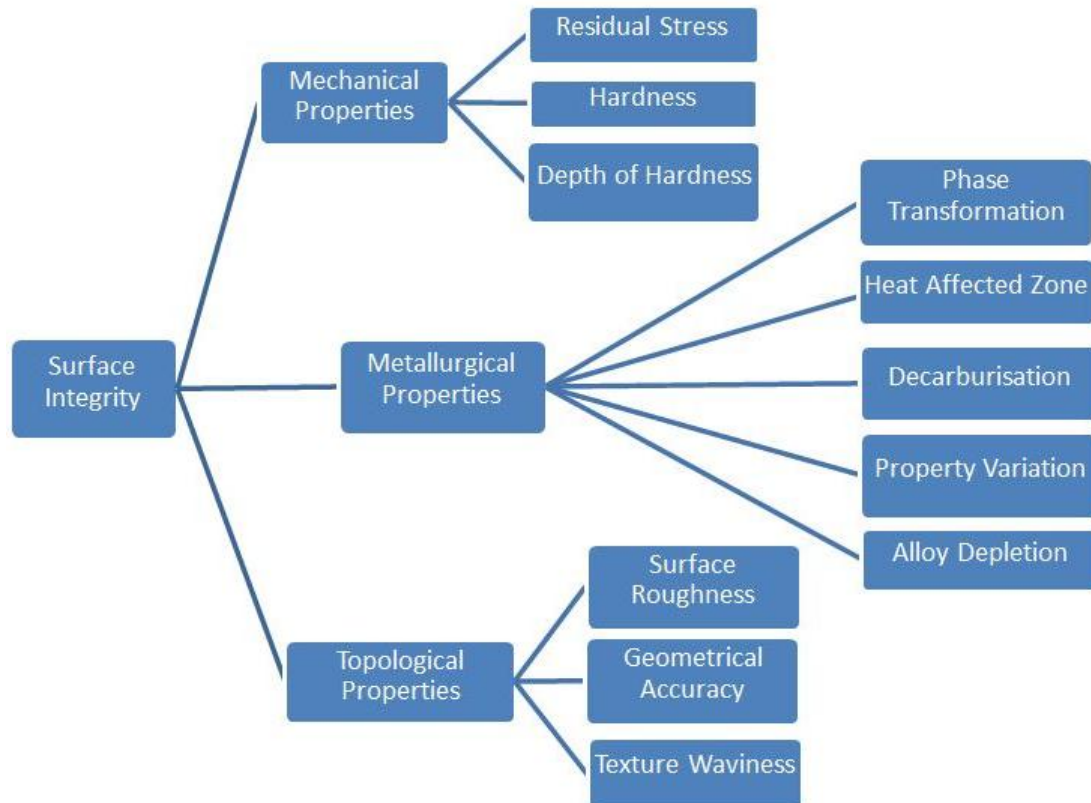


Figure 5, Surface integrity sub groups and parameters (Ulutan and Ozel 2011, Zurecki et al. 2003, Pusavec et al. 2011)

Many researchers have reported that using cryogenic coolant in the cutting process has resulted in a reduction in the surface roughness and tensile residual stress of the machined surfaces. Bhattacharyya and Horrigan (1998) studied the effect of cryogenic cooling in drilling Kevlar composites with HSS drills. The application of LN₂ improved surface integrity of the drilled holes regardless of the tool geometry by reducing the surface

roughness and geometrical deviations. Biermann and Heilmann (2010) used CO₂ snow to cool the aluminium alloy workpiece surface during face milling by a PCD cutting tools. It was found that this technique could result in a reduction in the surface roughness and burr size of the machined surface as compared to dry machining and compressed air cooling.

In cryogenic machining of different steels namely, AISI 4037, AISI 1040, AISI E4340, AISI 4041 and AISI C60 increased life and wear resistance of the cutting tools is one of the main reasons for improved surface finish. It is also responsible for reduction in the geometrical deviation as the cutting tool remains intact for a longer time during machining (Dhar et al. 2006b, Dhar and Kamruzzaman 2007, Dhar et al. 2002b, Dhar et al. 2002c, Dhar et al. 2006a).

Porous tungsten components for dispenser cathode manufacture are traditionally machined by using polymeric or copper infiltrant. These infiltrants act as a support for the pore structure and lubricant (Tarter et al. 2008). Tarter et al. (2008) and Pusavec (2012) reported that using LN₂ as coolant media in turning porous tungsten not only enhanced machinability by improving the tool life and surface finish, but also eliminates the requirement for infiltrant material. In addition, Pusavec (2012) noted that using cryogenic cooling not only improve the surface finish but also prevents smearing on the machined surface and produce less porosity on the machined surface as compared to conventional techniques.

Ke et al. (2009) noted that by using LN₂ as coolant in high speed milling of Ti64 with TiAlN coated WC tool, a 93.7% reduction in the surface roughness was achieved. Venugopal et al. (2003) noted that cryogenic cooling is an effective method to reduce the material re-deposition to the machined surface which can happen in dry turning of titanium alloys.

Pusavec et al. (2011) investigated the surface quality of machined Inconel® 718 under different environments, namely cryogenic LN₂, MQL, dry, integrated LN₂ spray and MQL.

They ranked the cutting environments based on their effectiveness on the surface finish (from

best to the worst) as: integrated LN₂ and MQL, LN₂, MQL. The highest surface roughness was produced as a result of dry cutting. Wang et al. (1996) found that in machining reaction bonded silicon nitride using LN₂ to cool the PCBN cutting tool led to a 84% reduction in the surface roughness. By using a similar cooling technique, surface roughness of a tantalum workpiece reduced by 40% in comparison with dry machining (Wang et al. 2002). By integrating plasma heating and LN₂ cooling in hybrid turning of Inconel® 718 using an SiC whisker reinforced alumina ceramic tool, Wang et al. (2003) enhanced the surface finish by 250% as compared to conventional dry machining.

Zurecki et al. (2004) studied the effect of cryogenic machining on surface integrity of heat treated and non-heat treated FN-0208 powder metallurgy steels with different densities. The hardness of the heat treated samples was higher than the non-treated samples. The samples were either machined conventionally by a low-content PCBN tool under flood coolant or by a TiN coated Al₂O₃-TiC black ceramic tool with LN₂ coolant. Investigations revealed that the cryogenically machined samples with lower hardness (non-treated) regardless of their density have a lower surface roughness than PCBN flood machined samples. Although in the case of heat treated samples, cryogenic machining with black ceramic tools has failed to improve the surface finish in comparison with conventional PCBN turning. In general, except for surface roughness, LN₂ cooling with ceramic tool improved the surface integrity by producing harder and denser surface, while in flood cooling the surface hardness was reduced after the cutting operation. This is attributed to the local tempering of the material at the cutting zone due to the high cutting temperature.

Formation of white layers is a thermo-mechanical defect which can occur during machining and is correlated to the materials true hardness (Zurecki et al. 2004). It is attributed to the dissolution of low alloy carbide particles into the austenitic matrix of the workpiece material, where catastrophic shear takes place as the operating mechanism resulting in carbide

refinement (Zurecki et al. 2003). Zurecki et al. (2004) found that there is a relation between the cutting forces and formation of the white layer. They identified that white layer forms when the value of R in the below equation becomes larger than 1.5.

$$R = \frac{(F_f^2 + F_n^2)^{\frac{1}{2}}}{F_c}$$

Where F_f is feed force, F_n is normal force and F_c is tangential force (Zurecki et al. 2004).

It has been found that an increase in the feed rate increases the depth and extent of the white layer. In addition, this could be controlled by monitoring the cutting zone temperature (Zurecki et al. 2003). Applying LN_2 as cooling media showed promising results in reducing the thickness of the white layer in machining AISI 52100 steel with 60HRC (Zurecki et al. 2003, Umbrello et al. 2011, Umbrello et al. 2012). Interestingly Dutra Xavier et al. (2011) reported that LN_2 coolant eliminated the white layer in machining AISI 52100 with 62HRC. Furthermore, other studies (Zurecki et al. 2003) indicated that while at lower feed rates alumina tools produced thinner white layers, at higher feed rates PCBN tools outperformed alumina tools. This could be explained by the low thermal conductivity of alumina in comparison with PCBN revealing the importance of contact temperature on the thickness of the white layer.

Unlike AISI 52100, the existence of white layer is claimed to improve the corrosion resistance of AZ31 magnesium alloy (Jawahir et al. 2011, Yang et al. 2011). Cryogenic burnishing of AZ31 Mg alloy and Co-Cr-Mo alloy resulted in finer grains on the burnished surface of the specimen as well as a thicker white layer and hardness resulting in higher corrosion resistance, compared to traditionally ground surfaces (Pu et al. 2011c, Yang et al. 2011). Similarly, in turning processes, cryogenic cooling led to formation of a white layer on the machined surface of the AZ31 Mg alloy workpiece with a 60% increase in the hardness when compared to dry machining (Pu et al. 2010, Pu et al. 2011b, Pu et al. 2011a).

In contrary to previously stated studies, LN₂ precooling of the workpiece in turning AISI 1020, AISI 304 (18-8) stainless steel and 99.99% pure titanium has been reported (Uehara and Kumagai 1968) to exacerbate the surface finish as compared with dry machined surfaces. In addition, Ahmed et al. (2007) stated that direct cryogenic cooling of the AISI 4340 steel workpiece together with the cutting tool resulted in higher surface roughness compared to dry machined samples.

Scanning Electron Microscopy (SEM) images of the cryogenically ground surfaces revealed that the cryogenic temperature reduced the sliding and enhanced material removal by shearing and ploughing (Benfredj et al. 2006). Ben Fredj et al. (2006) demonstrated that pouring LN₂ into the grinding zone when machining AISI 304 stainless steel could result in a 40% reduction in the surface roughness. Their study (Benfredj et al. 2006) also indicated that cryogenic grinding produced 180MPa and 215MPa lower parallel and perpendicular residual stresses than wet grinding. These enhancements resulted in improved corrosion resistance and fatigue life of the ground surface (Benfredj and Sidhom 2006). Paul and Chattopadhyay (1995) noted that grinding zone temperature plays an important role in controlling the residual stress. They found that LN₂ is an effective coolant in comparison with emulsion for reducing the grinding zone temperature and thus controlling residual stresses.

3.5 Effect of Cryogenic Machining with Respect to the workpiece material:

It is known that using cryogen as a cooling media in machining could improve machinability by increasing tool life, reducing cutting zone temperatures, improving surface finish, etc. Though, as discussed above, the effect of cryogenic cooling on machining operations is highly dependent on the tool/workpiece material pair. The aim of this section is to review the studies in cryogenic machining from the workpiece material point of view. This will help to find the appropriate requirements for a specific material type. The majority of studies in

cryogenic machining have concentrated on ferrous materials, polymers and super alloys including titanium and nickel based alloys. In this section materials are classified into steels, super alloys, composites, polymers and other materials.

3.5.1 Machining ferrous Materials:

A large body of research has been conducted on studying the effects of different cryogenic cooling methods on the machinability of different types of ferrous alloys. Chip formation and BUE are two phenomena which has made low carbon steels hard to machine, while excessive heat generation, short tool life and poor surface quality are usually associated with machining high carbon steels.

3.5.1.1 Low Carbon Steels:

Hong and Zhao (1999) and Hong and Ding (2001b) reported that cryogenic cooling of chips and the cutting zone in turning low carbon steels results in enhanced chip breakability and elimination of the BUE. Cryogenic temperatures increase the hardness, strength and reduce the fracture toughness and elongation percentage of the carbon steels. This ductility to brittleness transition is a distinctive characteristic of low carbon steels which in cryogenic machining enhances machinability. In machining AISI 1020 low carbon steel, studies by Uehara and Kumagai (1968, 1970) indicated that cryogenic cooling of the workpiece regardless of the cooling technique enhanced the chip breakability and eliminated BUE. In addition, they found that cryogenic cooling of the workpiece reduced the cutting forces and the flank wear width resulted in longer tool life. Despite improvements in the tool life and chip breakability, cooling the workpiece exacerbated the surface quality as compared to dry machining (Uehara and Kumagai 1968). Studies (Hong et al. 1999, Hong and Ding 2001b) revealed that cryogenic spraying on the chips and rake face of the cutting tool improved chip

breakability and tool life. In addition, it resulted in an 8% increase in the cutting forces and a reduction in the surface roughness. It has been noted (Hong et al. 1999) that at high cutting speeds the heat generated at the cutting zone surpassed the cooling effect of LN₂, therefore its effectiveness in chip breakability was reduced. At low and medium cutting speeds LN₂ effectively cooled the chips below their embrittlement temperature resulting in satisfactory chip breaking. In order to benefit from the lubrication effect of LN₂ in machining AISI 1018, Jun (2005) recommended that the cutting operation should be conducted at high speeds. He noted that at low cutting speeds, the cooling effect of LN₂ could result in over hardening of the workpiece material and thus increase the cutting forces, surpassing the lubrication effect.

3.5.1.2 Medium and High Carbon, Die and High Speed Steels:

Aggarwal et al. (2009, 2008a, 2008b) studied the effect of spraying LN₂ into the cutting zone in machining AISI P-20 medium carbon steel. They stated that despite the 10% increase in the material hardness, machinability improved by decreasing the radial and feed forces and power consumption. Rahman et al. (2003) investigated the effect of chilled air at -23°C in end milling AISI P-20 steel. Investigations revealed that the effectiveness of the cooling method is highly dependent on the cutting parameters. For instance, while the lowest tool flank wear was achieved at low feed rates and cutting speeds, it produced higher surface roughness as compared to conventional flood cooling. In addition, chilled air was found to be only beneficial in terms of improved surface finish at higher feed rates (0.02 mm/tooth) while at lower feeds, flood coolant was superior.

Brinksmeier and Glabe (2001) reported that cryogenic cooling doubled the tool life of single crystal diamond (SCD) tools as compared with dry cutting in turning AISI 1045 steel. In order to study the effect of inert environments on tool wear, the experiment was repeated under an argon atmosphere and showed that machining in an inert atmosphere does not have

any advantages over machining in air. Thus, the improvements in LN₂ cryogenic machining was credited to the super cold machining environment. Other research (Dhananchezian et al. 2009) indicated that cryogenic turning of AISI 1045 produced higher cutting forces than conventional dry machining when using multi-layer coated WC tools. While cryogenic machining increased cutting forces, it reduced the chip thickness by 15% resulting in up to a 30% increase in the shear angle improving machinability.

Dhar and Kamruzzaman (2007) and Dhar et al. (2002a, 2002b, 2002c, 2002d, 2006b) studied the effect of spraying LN₂ on the rake and flank faces along the auxiliary edges of the cutting tool on machinability of different types of steels including AISI 1040, AISI 1060, AISI 4037, AISI 4041, AISI 4320 and AISI 4340. The researchers reported that in general, cryogenic cooling resulted in reduced cutting zone temperature, longer tool life, reduced cutting forces, improved surface finish and lower geometrical deviation. Yet, the two latter improvements were mainly attributed to the reduction in tool wear rather than cryogenic temperature.

It has been noted (Hong and Zhao 1999) that increases in the carbon content in steels up to 0.24% improves machinability by increasing brittleness enhancing chip formation. However, carbon content beyond 0.24% results in high material strength and produces large amounts of carbide particles which are responsible for abrasive wear. In addition high carbon steels do not show temperature embrittlement characteristics (Uehara and Kumagai 1968). Hence the cryogenic temperatures fail to enhance machinability as hardness and strength increases sharply by lowering the temperature, while the fracture toughness and elongation percentage reduces gradually (Hong and Zhao 1999). Zhao and Hong (1992) recommended that the most appropriate method to cryogenically machine high carbon steels is to inject the cryogen media into the cutting zone rather than cooling the workpiece. Paul et al. (2001) reported that spraying LN₂ into the cutting zone resulted in a 2.5 times increase in the uncoated WC tool life in turning AISI 1060 steel in comparison with emulsion machining.

Ghosh et al. (2003) examined the machinability of AISI 52100 steel under cryogenic and dry environments in turning with TiN coated Al₂O₃ cutting tool. It has been observed that under cryogenic conditions, the cutting tool lasted twice as long as its counterpart in dry cutting. In addition, the researchers noted that cryogenic cooling produced a uniform and predictable wear making it easier to predict tool life. Furthermore, cryogenic machining makes it possible to machine components with surface roughness lower than 0.38 μ m with a flank wear limit of 0.6mm. Dutra Xavier et al. (2011) stated that spraying LN₂ into the cutting zone in machining AISI 52100 bearing steel improved tool life significantly and reduced the chip-tool contact area by 26%. In addition, they noted that spraying LN₂ did not affect the surface roughness and also extinguished the formation of the white layer on the machined surface. Investigations by Zurecki et al. (2004) revealed that cryogenic cooling improves the machinability of powder metallurgy steel using TiN coated alumina cutting tools. In this study cryogenic machining improved tool life by a factor of 5 and considerably reduced plastic deformation and smearing on the machined surface. In addition, LN₂ cooling retained the surface hardness of the component, while in dry cutting it reduced after machining due to local tempering due to the high cutting temperature. Crater wear on the rake and abrasion on the flank faces was defined as the main tool wear mechanisms in cryogenic turning of metallurgy powder steel with 32HRc hardness.

3.5.1.3 Stainless Steels:

The main problem in machining stainless steels such as AISI 304 and AISI 316 is their high material strength, high toughness and low thermal conductivity. In addition, lowering their temperature increases their strength and hardness significantly, while gradually reducing their fracture toughness. Hence, cooling the material hinders overall machinability (Uehara and Kumagai 1968, Uehara and Kumagai 1970). Due to these characteristics, Hong and Broome

(2000) suggested cooling the cutting zone in order to improve machinability. An uncoated WC cutting tool was used to machine AISI 304 workpieces. Cryogenic cooling of the cutting zone exhibited up to 67% longer tool life than wet machining. In addition, the cryogenically cooled cutting tool could withstand higher cutting speeds of 3.82m/sec, where its counterpart under dry and wet conditions failed by catastrophic fracture. Kalyan Kumar and Choudhury (2008) demonstrated a 14.8% and 37.39% reduction in the cutting forces and tool flank wear by using LN₂ in turning AISI 202 stainless steel with PVD TiN coated WC tool. Hong and Broome (2000) reported that in machining AISI 304 stainless steel, spraying LN₂ into the cutting zone increased tool life by 67%. In addition, they found that cryogenic cooling is more favourable at high cutting speeds, while emulsion cooling performs better at lower cutting speeds. Similar conclusions were drawn by Khan and Ahmed (2008) and Khan et al. (2010) where cryogenic cooling resulted in up to a four times improvement in the TiCN coated WC tool. Nalbant and Yildiz (2011) used an external nozzle to inject LN₂ into the cutting tool in milling AISI 304 stainless steel with uncoated carbide tools. They reported that cryogenic cooling resulted in increased cutting forces and spindle torque, but did not change the tool failure mechanism as compared to dry cutting. They concluded that cryogenic machining does not show significant advantages over dry machining.

3.5.2 *Machining Special Alloys:*

The majority of studies in cryogenic machining of special alloys have concentrated on titanium and nickel alloys. These alloys exhibit distinctive characteristics making the machining of these materials relatively difficult. These alloys are chemically reactive to most known tool materials. Very low thermal conductivity results in extremely high temperatures at the cutting zone. By considering the high thermal stability and hardness of the material,

increased cutting temperatures do not help workpiece material softening. High temperatures at the cutting zone have led to severe tool wear and short tool life.

3.5.2.1 Titanium Alloys:

Using cryogenics as a cooling media in the machining of titanium alloys has been studied for several years. Uehara and Kumagai (1968, 1970) investigated the effect of cryogenic cooling of the workpiece in the machinability of 99.99% pure titanium. They reported that cryogenic cooling extended tool life (Uehara and Kumagai 1970), but increased cutting forces and reduced surface finish (Uehara and Kumagai 1968). Ti64 can maintain a large portion of its ductility and toughness at low temperatures and does not exhibit low temperature embrittlement. Accordingly, Hong and Zhao (1999) suggested that freezing cutting tool is more favourable than freezing the workpiece. However, considering the chemical reactivity of titanium, the researchers pointed that cooling the workpiece in addition to the cutting tool can be beneficial by reducing chemical reactivity between the workpiece and tool materials. In addition, freezing the cutting tool enhances the mechanical properties and chemical stability of the cutting tool material whilst it can reduce the friction at cutting Zone.

For their experiments, Hong and Zhao (1999) used a nozzle spraying LN₂ into the cutting zone to reduce cutting temperatures, while preventing over hardening of the workpiece material. The researchers reported that five times improvement in tool life has been achieved using this system. It has been reported that spraying LN₂ into the cutting zone reduces the cutting temperature significantly as compared to dry and wet machining (Dhananchezian and Kumar 2011, Hong and Ding 2001a).

Hong and Ding (2001a) empirically investigated the effectiveness of different LN₂ cooling methods in terms of reducing the tool-chip contact temperature. The cooling approaches were then ranked in terms of effectiveness (best to worst) as i) simultaneous LN₂ cooling of rake

and flank faces, ii) LN₂ cooling of rake face, iii) LN₂ cooling of flank face and iv) indirect LN₂ cooling of the cutting tool (Hong and Ding 2001a). It is noteworthy to mention that in their experiments, emulsion cooling performed better than indirect cryogenic cooling. A similar order has been observed (Hong et al. 2001b) when tool life was of interest.

Machai and Biermann (2011) used LCO₂ to cool the cutting zone in machining Ti-10V-2Fe-3Al alloy using (TiAl)N-TiN coated WC tool with CNMG 120404 geometry. They reported that using LCO₂ reduced flank wear geometries and resulted in a two times improvement in tool life. In high speed milling of Ti64, Ke et al. (2009) reported that cryogenic cooling of the cutting zone using LN₂ is an effective method to reduce the BUE and prevent the adhesion of chips to the machined surface. In their experiments, cryogenic cooling resulted in a 93.7% reduction in the surface roughness and a 32.7% reduction in cutting forces.

Birmingham et al. (2011b) investigated the determination of optimal cutting parameters in cryogenic turning of Ti64 alloy using Seco WNMG 120408 MF1 tungsten carbide tool. The main tool failure mode regardless of the cutting environment was crater wear, either limited to the tool nose at high feed rates or distributed along the rake and nose at low feed rates. Based on the cutting parameters the application of LN₂ into the cutting zone resulted in a 43% to 58% improvement in tool life. The biggest improvement in tool life was achieved at high feed rates and low depths of cut. Low feed and high depth of cut yielded the longest tool life. The researchers concluded that controlling heat generation by precise selection of cutting parameters is more important than heat dissipation through the application of LN₂. Pusavec and Kopac (2009) reported that by using LN₂ as a coolant, the cutting tool could withstand higher cutting speeds as compared to dry and emulsion cutting. Venugopal et al. (2003) studied the effects of TiB₂ coating on the machinability of Ti-5Al-5Mo-2Sn-V alloy under dry and cryogenic conditions. They reported that while cryogenic cooling generally improved machinability, TiB₂ coating is not appropriate for machining titanium alloys as it cannot

withstand the fluctuating cutting forces and cutting temperatures. Based on their studies, despite the higher costs of LN₂ in comparison with emulsion and dry machining, cryogenic machining can reduce machining costs by up to 70%.

In end milling of Ti64 alloy using solid carbide cutting tools, researchers (Shokrani et al. 2012c, Shokrani et al. 2012d) reported that spraying LN₂ into the cutting zone can significantly improve surface roughness and tool life without noticeable increase (3%) in power consumption of CNC machine tool. In their studies (Shokrani et al. 2012d) cryogenic cooling has resulted in up to a 59% reduction in surface roughness in comparison with conventional flood cooling. Using TiAlN coated solid carbide end mill, they reported that the main tool failure mode was chipping of the cutting edge which was less significant in the case of cryogenic machining whilst lower flank wear was observed on tool used for cryogenic machining.

Based on the studies in cryogenic machining of titanium alloys it can be found that regardless of the cooling technique, cryogenic coolant exhibits promising improvements in tool life. However, in order to enhance the surface finish in the machining zone the best approach is to penetrate the cryogen into the cutting zone.

3.5.2.2 Nickel Based Alloys:

The majority of studies in machining nickel based alloys have concentrated on Inconel® 718. This is due to the high usage of this material in the hot regions of aerospace engines and gas turbines where other materials cannot withstand high temperatures. Wang and Rajurkar (2000) studied the effect of cryogenic cooling of the cutting tool through a cap placed over the cutting insert. Cryogenic cooling in machining Inconel® 718 improved the surface finish and reduced tool flank wear significantly. Flank wear was 0.85mm after a 62mm cutting length in dry cutting, whereas cryogenic cooling produced 0.6mm flank wear after 110mm of

cutting. While the researchers did not conduct comparable measurements, the results showed the effectiveness of cryogenic cooling on tool life. Pusavec et al. (2011) reported that spraying LN₂ into the cutting zone enhances the surface integrity of the Inconel® 718 component. The enhancements were defined as lower surface roughness, increased surface and sub-surface hardness, higher compressive residual stresses and a thicker residual stress affected zone. In addition, by applying LN₂ into the cutting zone higher cutting speeds become available resulting in up to a 63% reduction in the machining time (Pusavec et al. 2010).

Wang et al. (2003) integrated plasma heating of the workpiece and LN₂ cooling of the cutting tool in turning of Inconel® 718 with silicon carbide whisker-reinforced Al₂O₃. In this technique the workpiece was heated by a plasma beam and softened just before the cutting operation. In addition, the hardness and strength of the cutting tool was increased due to the cryogenic temperature. Wang et al. (2003) noted that this technique has led to 250% reduction in the surface roughness and 156% longer tool life in comparison to conventional dry cutting. Studies showed that in plasma enhanced machining the cutting tool suffered from excessive flank wear as compared to dry machining due to higher cutting temperatures. Cryogenic cooling of the cutting tool in plasma enhanced machining increased tool life up to 170%. This study indicates that plasma enhanced machining is not an effective method for machining Inconel® 718. This could be explained by Inconel® 718's very low thermal conductivity, where plasma heating increases the cutting temperature drastically resulting in thermally induced tool failure. It was reported that cryogenic plasma enhanced turning, produced 30%-50% less cutting forces than conventional dry machining. This is attributed to (i) lower material hardness and strength due to plasma heating (ii) higher tool hardness and wear resistance resulted in lower friction and tool wear.

Truesdale and Shin (2009) noticed that smearing and plucking are two main surface defects that affect the performance life of components made from Udimet 720 nickel based alloys. The researchers found that in wet milling an increase in the feed rate and cutting speed can result in increased plucking and smearing respectively. Accordingly, machining Udimet 720 is associated with very conservative cutting parameters and high machining costs. They reported that under cryogenic cooling at 120m/min, similar surface quality was produced as 10m/min in dry cutting. Despite reductions in the tool life and 84% increase in tool change cost, cryogenic cooling of the workpiece resulted in a 90% reduction in the total machining cost through an 1100% increase in the cutting speed. Similarly in CNC milling of Inconel® 718, Shokrani et al. (Shokrani et al. 2012a) reported that while cryogenic cooling has failed to improve tool life, significant (33%) reduction in surface roughness has been achieved. The main tool failure mechanism in their study was reported to be chipping and catastrophic failure of cutting edge, thus they recommended that further studies on machining parameters and cutting tool geometry is required.

3.5.3 Aluminium Composites and Alloys:

Studies on the cryogenic machining of aluminium alloys are very limited. This could be explained by the fact that generally aluminium alloys are considered as easy to cut materials. However, it should be noted that in order to step into the more environmentally friendly machining techniques aluminium should be particularly considered, due to the increased use of aluminium components in different aspects of life and industry. In addition, aluminium is highly thermally dependant and produces many difficulties in dry machining. Aluminium alloys are usually machined using emulsion environment. More information about the health hazards and environmental effects of using conventional cutting fluids can be found in Shokrani et al. (2012b).

Dhananchezian et al. (2009) studied the impacts of injecting LN₂ into the cutting zone in turning 6061-T6 aluminium alloy using uncoated WC cutting tools. They noted that while cryogenic machining produced 10% higher cutting forces than emulsion cooling, it reduced cutting temperature by up to 39% as compared to emulsion cooling. In addition, it resulted in a 25% reduction in the chip thickness and a 30% increase in the shear angle. It can be concluded that despite the increase in the cutting forces, cryogenic cooling improved the machinability of 6061-T6 aluminium alloy. In another study, Dhokia et al. (2012a) reported that spraying LN₂ over the machining surface in CNC milling of 6061-T6 aluminium surface roughness has been reduced by as much as 50% as opposed to conventional dry and wet conditions whilst chip re-deposition and BUE was eliminated. Biermann and Heilmann (2010) studied the effect of CO₂ snow cryogenic cooling on the surface roughness and burr size of aluminium 6068-T6 face-milled surface. They investigated two cryogenic cooling concepts namely (i) stationary cooling of the exit edges and (ii) cooling nozzles moving with feed rate. Empirical studies revealed that the surface roughness of the machined surfaces under a cryogenic environment is significantly lower than dry and compressed air cooled environments. It should be noted that while the smallest burr size was produced using the first concept, the second concept produced the lowest surface roughness. The researchers noticed that the effectiveness of the stationary cooling method is limited to simple shapes and cannot be utilised for complex shapes consisting of several edges. They concluded that the best method to reduce the burr size and surface roughness in machining complex shapes is to use a cooling device which moves with the cutting tool and is fixed with respect to the feed motion of the tool.

Another type of aluminium based materials subjected to cryogenic machining are aluminium alloys or aluminium matrix composites containing silicon particles. The presence of silicon phase/particles in the material structure of aluminium alloys/composites increases the wear

50

resistance, hardness and strength of the material. Although the presence of hard and abrasive silicon carbide particles, which are harder than WC tools has resulted in excessive tool wear (Hong and Zhao 1999, Tanaka and Akasawa 1999, Liu and Kevinchou 2007, El-Gallab and Sklad 1998, Davim 2002). Hong and Zhao (1999) argued that cryogenic cooling of A390 aluminium workpiece could increase material strength and hardness of the abrasive silicon phase. They recommended freezing the cutting tool in order to enhance wear resistance and hardness of the tool material. Liu and Kevinchou (2007) used a vortex tube to produce chilled air for turning of A390. They found that while chilled air cooling generally increases tool life, the effectiveness of the system is highly process parameter dependant. For instance, while chilled air cooling at a cutting speed of 5mm/sec reduced the flank wear by up to 20%, the improvements at the higher and lower cutting speeds is not significant. This can be explained by the poor thermal conductivity and low cooling capacity of air. Lin et al. (2001) studied the effect of cryogenic cooling, SiC content and heat treatment in the machinability of 356Al/SiC metal matrix composite. They reported that an increase in the SiC content in the material increases the flank wear rate, while the applications of cryogenic coolant on the PCD cutting tool material regardless of the silicon content and heat treatment improved surface finish and tool life.

3.5.4 Polymers:

The main application of cryogenic cooling in machining of polymers is to freeze the workpiece material so as to enhance machinability. This is attributed to the distinctive ductile to brittle characteristic change of polymers at low temperatures known as glass transition temperature. Cryogenic temperature reduces the ductility and elongation percentage of the material, thus enabling it to withstand the cutting forces without deformation. Dhokia et al. (2010) used LN₂ to freeze ethylene-vinyl acetate (EVA) for milling sculptured surfaces such

as shoe insoles. They noted that by freezing the workpiece it becomes possible to machine a single personalised shoe insole which is traditionally manufactured by expensive and time consuming injection moulding. Kakinuma et al. (2008) designed a special fixture to cool PDMS workpieces for manufacturing micro-fluidic chips. Micro fluidic chips are usually manufactured through photolithography and a micro-moulding process. Cryogenic freezing of the material has made it possible to machine micro-fluidic chips by a micro-milling operation. However, tool run out and material shrinkage at ultralow temperatures result in geometrical deviations. Kakinuma et al. (2008) found that the desired surface roughness could be achieved by selecting a high spindle speed (20000rpm), low feed rate (1mm/min) and low depth of cut (10 μ m). Mishima et al. (2010) suggested that in cryogenic machining of PDMS, dimensional inaccuracies can be compensated by considering the thermal shrinkage of the material. They also successfully deformed and then froze the workpiece in order to manufacture different shapes such as bent holes and channel grooves with different shapes. The pictorial process of machining a bent hole with pre-deformed material using cryogenic freezing is shown in figure 6.

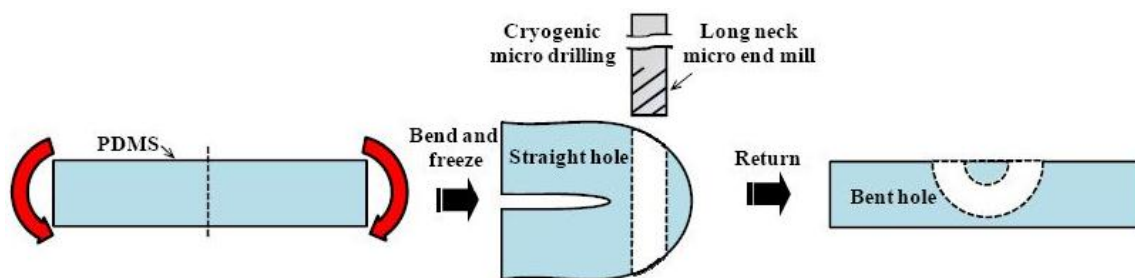


Figure 6, Pre-deformed bent hole manufacturing process using LN₂ cryogenic freezing (Mishima et al. 2010)

3.5.5 *Ceramics:*

Most of the cryogenic machining experiments on the ceramics have concentrated on machining reaction-bonded silicon nitride Si_3N_4 (RBSN). This material exhibits high wear resistance, high strength together with poor thermal conductivity even at high temperatures. These characteristics can result in high temperature concentration at the cutting zone. As RBSN has very high hot hardness, elevated temperatures fail to soften the material and enhance the material cutting process. In contrary, most cutting tools fail at elevated temperatures and suffer from heat softening (Wang et al. 1996, Wang and Rajurkar 2000). The wear resistance of the RBSN is higher than most cutting tool materials. Based on the studies by Wang et al. (1996) only diamond and PCBN tools have wear resistance higher than RBSN. However, diamond is unstable at high cutting temperatures. By cooling the cutting tool using LN_2 , it has been reported (Wang et al. 1996, Wang and Rajurkar 2000, Wang and Rajurkar 1997) that significant improvement in tool life can be achieved. Investigations on the tool wear mechanism revealed that while LN_2 cooling eliminated the chipping and fracture on the cutting edge as seen in dry cutting, the main tool failure mode regardless of cooling method was flank wear (Wang et al. 1996). In addition, it has been found that among different types of PCBN tools, CBN50 exhibited the longest tool life followed by VC722 and VC734 in decreasing order (Wang and Rajurkar 2000). Cryogenic cooling also enhanced the average surface roughness by 84% along a 40mm length of cut. It is clear that in this case the surface roughness is highly affected by tool wear, as for the same length of cut the flank wear of the tool in dry cutting was 5 times bigger than that of cryogenic machining (Wang et al. 1996). As a result, it cannot be concluded that the enhancements in the surface roughness is directly due to cryogenic cooling.

3.6 Critique and Research Gaps:

The application of cryogenics in material cutting processes can be classified into: i) Cryo-processing of the cutting tools and ii) Cryogenic Machining. These categories with related areas of study and research requirements are illustrated in figure 7. In this section these categories are critiqued and the areas of investigation are defined.

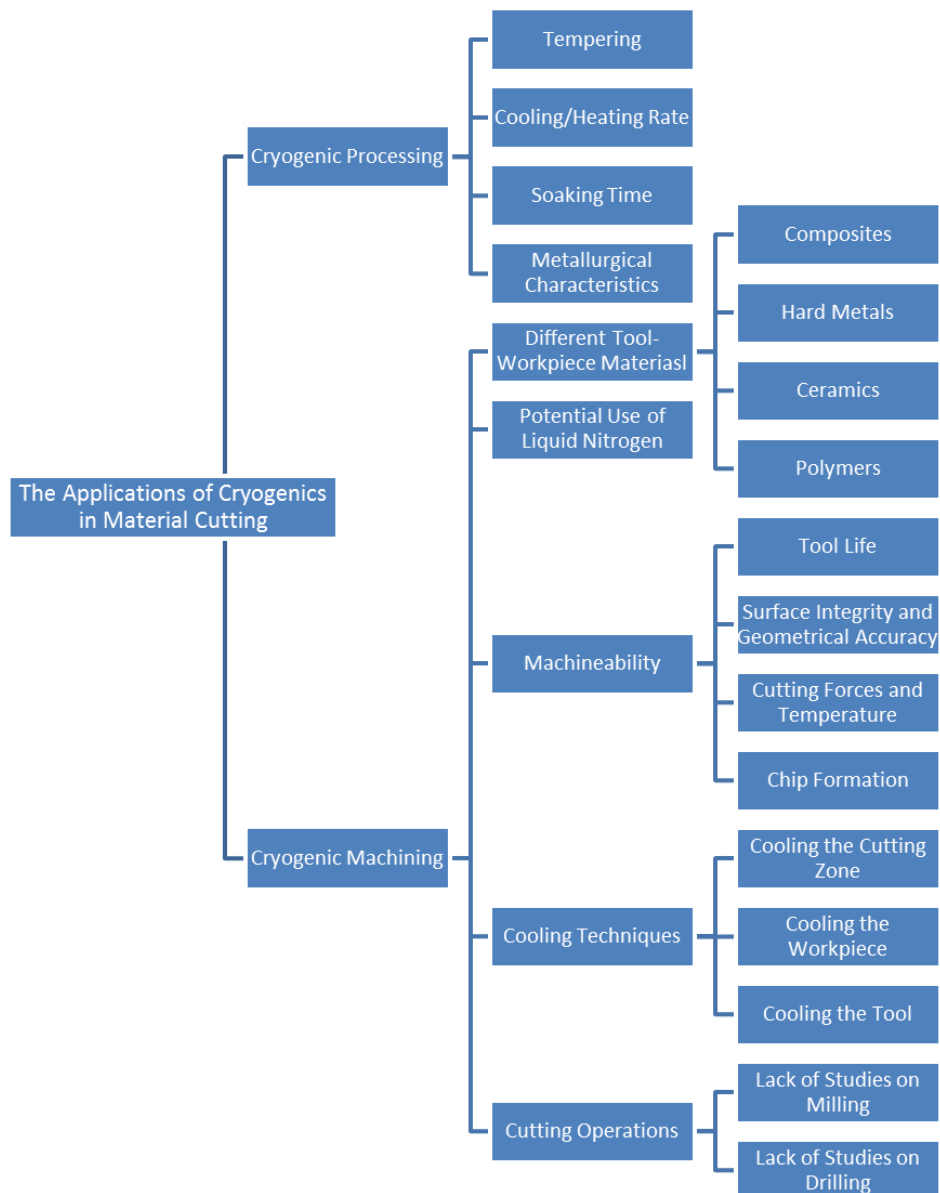


Figure 7, Areas of study and classification of the applications of cryogenics in material cutting

3.6.1 Cryogenic processing:

Based on the literature, cryogenic treatment of the cutting tools is found to be an effective method for enhancing the strength, hardness and wear resistance of HSS and WC cutting tools. However, while retained austenite transformation and carbide precipitation are defined by researchers as the main reasons behind the improvements of the cryogenically treated HSS tools, it failed to explain the improvements of the treated WC tools. Thus, it can be stated that the factors for explaining improvements in cryogenically treated cutting tools are still unclear and requires further studies on the metallurgy and microstructure of the treated materials.

It is known that some changes in the material microstructure happen in cooling to and heating from cryogenic temperature as well as when the material is soaked into the cryogen (Kalia 2009). Though, the optimum cooling and heating rates and the soaking time is still unclear. The literature showed that tempering before and after the cryogenic treatment can affect the effectiveness of the treatment process to differing extents. Although the effects were in contrast among different studies such as: (Firouzdor et al. 2008, Molinari et al. 2001, Leskovsek et al. 2006). Thus, further studies are required to understand, clarify and define the effects of tempering and tempering temperature on the performance of the cutting tools.

Table 3 summarises the studies on the effects of cryogenic treatment on the performance of cutting tools. It is clarified that all studies on the cryogenic treatment of the cutting tools are concentrated on HSS and WC tools and there is no report on the effect of cryogenic treatment on the performance of other cutting tool materials.

3.6.2 Cryogenic Machining:

As shown in Figure 8, while the studies on cryogenic machining date back to the early 20th century and were preceded by the mid-20th, when the first liquid gas fuelled rockets were launched, the majority of the studies have been conducted during years 2000 onwards.

Table 3, Summary of the researches on the effect of cryogenic treatment on the performance of the cutting tools

Authors	Cooling Media	Machining Condition	Operation	Treated Cutting Tool	Workpiece
Ramji et al. 2010	LN ₂		Drilling	HSS	Grey Cast Iron
Sreeramareddy et al. 2009	LN ₂	Dry	Turning	TiN-TiCN-Alumina-TiN coated WC	C45
Firouzdor et al. 2008	LN ₂	Dry	Drilling	HSS	AISI 1040
Dasilva et al. 2006	LN ₂	Wet and Dry	Drilling, milling and turning	TiN coated and Uncoated HSS	AISI 1020
Leskovsek et al. 2006	LN ₂	Dry	Sliding	HSS	Silicon Nitride ceramic balls
Yong et al. 2006	LN ₂	Wet and Dry	Face milling	Uncoated WC	Ti-6Al-4V
Stewart 2004	LN ₂	Dry	Turning	Uncoated WC	MDF
Seah et al. 2003	LN ₂	Dry	Turning	Uncoated WC	ASSAB 760
Molinari et al. 2001	LN ₂	Dry	Sliding	AISI M2 HSS	Hardened 100Cr6 steel

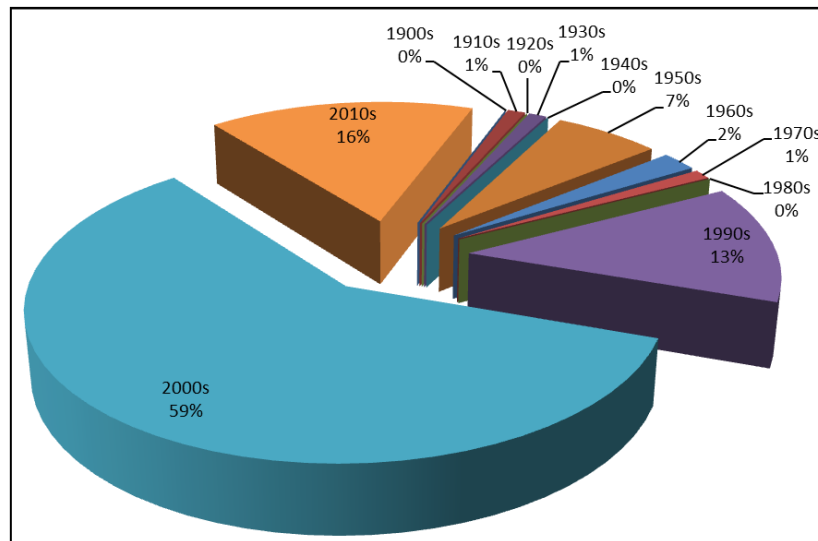


Figure 8, Distribution of the collected papers based on the publication year

Despite the long history of cryogenic machining, its advantages over dry and flood cooling and the introduction of some commercial cryogenic machining equipment (MAG 2012, Air-Products 2011), this technique is not popular among industrialists. This could be explained by the fact that most studies in this area have concentrated on the turning of steel materials using LN₂, as illustrated in figure 9.

Unlike conventional cutting fluids, cryogens cannot be cycled in the machine tool and reused in the cutting operations therefore economical use of the cryogen is very important. The most economical approach for cryogenic machining is to deliver the cryogen to the exact point. Another step towards realising the use of cryogenic machining in industry is to extend its application into other cutting operations, such as milling and drilling, using more common materials such as aluminium alloys. As mentioned before and illustrated in figure 9, majority of studies on the cryogenic machining of hard metals have concentrated on turning operations. It is true that turning is one of the most common operations in any manufacturing process, though milling operations are more significant in mainstream CNC manufacturing.

In addition, except studies by Bhattacharyya and Horrigan (1998) on drilling Kevlar composites, Ke et al. (2009) on helical high speed milling of holes and Dhokia et al. (2012b) on drilling carbon fibre composites, to the best of the author's knowledge, there is no study on the effect of cryogenic cooling in drilling operations. This is mainly due to the difficulties of gaining access to the cutting tool and modification in drilling and milling as compared to turning where the cutting tool can be modified or an external nozzle can be focused on the cutting zone more easily.

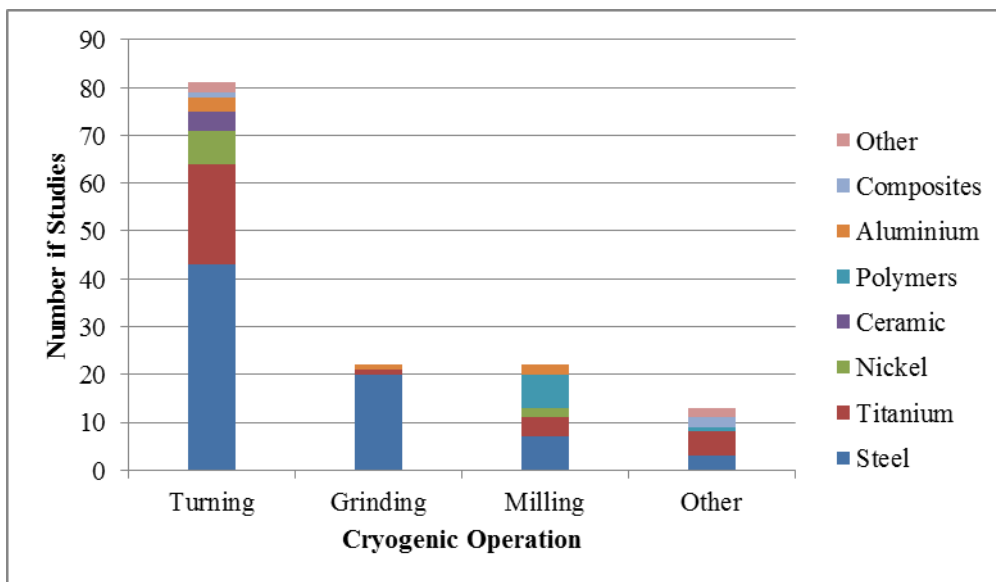
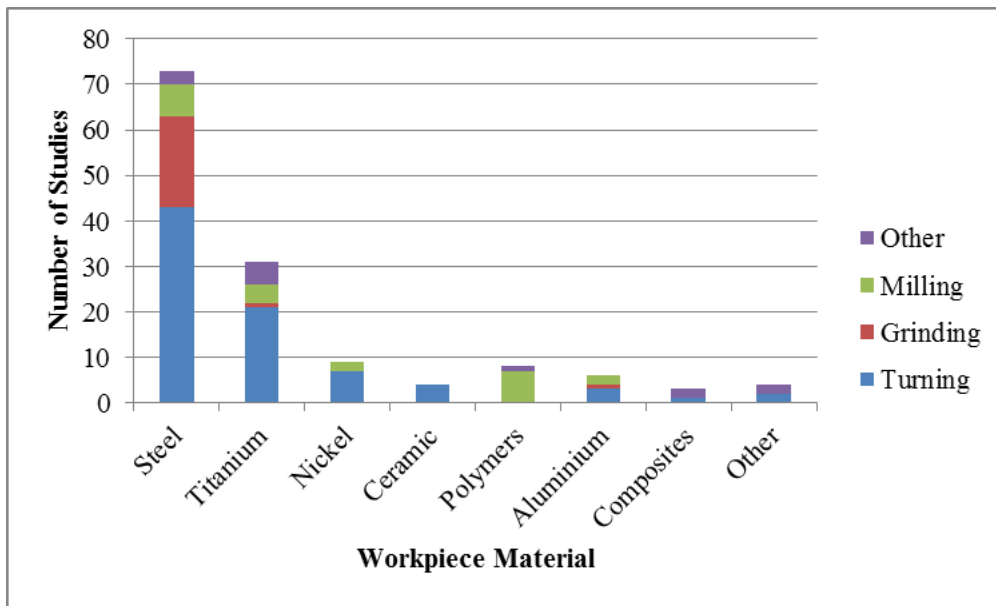


Figure 9, Distribution of the collected studies on cryogenic machining based on the workpiece materials and cutting operations

Compared to single point turning, milling inherently is an intermittent operation with increased degrees of freedom enabling significantly more complex parts to be machined (Dhokia 2009). Thus, focusing an external nozzles or modifying the cutting tool is relatively more complex and could consist of changes in the design of the machine tool. These technical issues together with cost implications of the CNC machining centres and unwillingness of

industry to adapt new systems are responsible for the lack of knowledge, slow improvements and adoption of cryogenic machining.

Most researchers in cryogenic machining have used LN₂ as the cryogen in their experiments. The main benefits of LN₂ over other liquid gases can be defined as follows. Nitrogen is a colourless, odourless and inert gas which forms 78% of the air. Nitrogen is lighter than air so it disperses into the atmosphere easily so reduces the requirements for extra ventilation at the shop floor. LN₂ is a relatively cheap liquid gas with a boiling temperature, much lower than LCO₂ with proven lubrication capabilities, which in machining is accompanied with reductions in tool-chip contact length resulting in lower cutting forces.

In machining hard materials where the tool life and surface quality is of interest, most researchers have used an external nozzle or modified cutting tool/tool holder to inject the cryogen into the cutting zone.

In machining ductile materials and polymers, the main goal of using cryogenics is to make the workpiece material brittle so as to enhance the chip formation and cutting operations. In such cases, for ductile materials such as low carbon steels Hong et al. (1999) suggested focusing the cryogen nozzle onto the chip to make it brittle and enhance chip breakability. Although in machining polymers, where the workpiece material deforms due to cutting forces, the workpiece should be frozen in order to enhance machinability (Dhokia et al. 2010). It should be noted that in this case the workpiece material should be soaked in a cryogen bath. There is no study on the effect of freezing the cutting point rather than the whole material in machining polymers in order to reduce cryogen consumption.

As shown in figure 9 the extent of the workpiece materials used for the cryogenic machining research is very limited and is mostly concentrated on steel materials. Tables 4 to 7 compile a summary of studies on cryogenic machining of different types of steels, namely low carbon steels, high carbon steels, tool and die steels and stainless steels. Among the 5 studies on

59

cryogenic milling of steel workpieces, only Nalbant and Yildiz (2011) used LN₂ for machining AISI 304 stainless steel.

Table 4, Compilation of the studies on the effect of cryogenic cooling on the machinability of low carbon steels (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperatures, C: chip formation)

Author	Cryogen	Operation	Tool	Workpiece	Area of Study				
					S	F	L	T	C
Hong 2006	LN ₂	Sliding	Different Coatings	AISI 1018		X	X		
Paul and Chattopadhyay 2006	LN ₂	Turning	Uncoated WC	AISI 1020	X	X	X	X	
Jun 2005	LN ₂	Turning	Uncoated WC	AISI 1018	X	X			
Dhar et al. 2002a	LN ₂	Turning	Uncoated WC	AISI 4320		X		X	X
Hong et al. 2002	LN ₂	Sliding	TiC-TiN-TiCN coated and uncoated WC	AISI 1018					
Hong and Ding 2001b	LN ₂	Turning	Uncoated WC	AISI 1008	X	X	X	X	X
Hong et al. 1999	LN ₂	Turning	Uncoated WC	AISI 1008				X	X
Paul and Chattopadhyay 1996a	LN ₂	Grinding	A60K5V wheel	AISI 1020				X	
Paul and Chattopadhyay 1996b	LN ₂	Grinding	A60K5V wheel	AISI 1020		X			X
Paul and Chattopadhyay 1995	LN ₂	Grinding	A60K5V wheel	AISI 1020	X	X		X	X
Uehara and Kumagai 1970	LN ₂	Turning	HSS	AISI 1020	X	X	X	X	
Uehara and Kumagai 1968	LN ₂	Turning	HSS	AISI 1020	X	X	X	X	

Table 5, Summary of the studies on the effect of cryogenic cooling on the machinability of medium and high carbon steels (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperatures, C: chip formation)

Author	Cryogen	Operation	Tool	Workpiece	Area of Study				
					S	F	L	T	C
Dhananchezian et al. 2009	LN ₂	Turning	Multi coated WC	AISI 1045	X	X	X	X	
Abele and Schramm 2008	LCO ₂	Turning	PCD	Compacted graphite iron		X	X	X	
Ahmed et al. 2007	LN ₂	Turning	Uncoated WC	AISI 4340	X		X		
Dhar and Kamruzzaman 2007	LN ₂	Turning	TiCN-Al ₂ O ₃ coated WC	AISI 4037	X		X	X	
Dhar et al. 2006b	LN ₂	Turning	Uncoated WC	AISI 1060	X		X		
Dhar et al. 2002a	LN ₂	Turning	Uncoated WC	AISI 1040		X		X	X
Dhar et al. 2002b	LN ₂	Turning	Uncoated WC	AISI 1040 and E4340	X		X	X	
Dhar et al. 2002c	LN ₂	Turning	Uncoated WC	AISI 4041	X	X	X	X	
Dhar et al. 2002d	LN ₂	Turning	Uncoated WC	AISI 1040		X		X	
Brinksmeier and Glabe 2001	LN ₂	Turning	Single Crystal Diamond	AISI 1045			X		
Paul et al. 2001	LN ₂	Turning	Uncoated WC	AISI 1060	X		X		

There is a significant lack of research on the cryogenic machining of composite materials. The only notable studies in cryogenic machining of synthetic composites has been conducted by Bhattacharyya and Horrigan (1998) and Dhokia et al. (2012b) where substantial improvements in machinability have been reported. Although, in the study by Bhattacharyya and Horrigan (1998) due to the use of a new cutting tool together with cryogenic coolant and lack of methodical experimental design the underlying reasoning behind the improvements has remained unclear.

Table 6, Summary of the studies on the effect of cryogenic cooling on the machinability of die, tool and high speed steels (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperatures, C: chip formation)

Author	Cryogen	Operation	Tool	Workpiece	Area of Study				
					S	F	L	T	C
Umbrello et al. 2012	LN ₂	Turning	CBN	AISI 52100	X				
Ravi and Kumar 2011	LN ₂	End milling	TiAlN coated WC	AISI H13	X	X	X	X	X
Dutra Xavier et al. 2011	LN ₂	Turning	PCBN	AISI 52100	X		X		
Aggarwal et al. 2009	LN ₂	Turning	TiN coated WC	AISI P20		X			
Aggarwal et al. 2008a	LN ₂	Turning	TiN coated WC	AISI P20	X	X	X		
Aggarwal et al. 2008b	LN ₂	Turning	TiN coated WC	AISI P20					
Paul and Chattopadhyay 2006	LN ₂	Grinding	A60K5V wheel	AISI M2	X	X		X	
Paul and Chattopadhyay 2006	LN ₂	Turning	Uncoated WC	AISI H11 and D2	X	X	X	X	
Zurecki et al. 2004	LN ₂	Turning	TiN coated black ceramic and PCBN	powder metallurgy steel	X	X	X		
Ghosh et al. 2003	LN ₂	Turning	TiN coated Alumina	AISI A2	X	X	X		
Ghosh et al. 2003	LN ₂	Turning	PCBN	AISI 52100	X		X		
Zurecki et al. 2003	LN ₂	Turning	TiN coated black ceramic and PCBN	AISI 52100 and A2	X				
Murthy et al. 2000	LN ₂	Grinding	A50K5V10 wheel	AISI A128	X	X		X	X
Paul and Chattopadhyay 1996a	LN ₂	Grinding	A60K5V wheel	AISI M2, D2 and H11				X	
Paul and Chattopadhyay 1996b	LN ₂	Grinding	A60K5V wheel	AISI M2, D2 and H11					X
Paul and Chattopadhyay 1995	LN ₂	Grinding	A60K5V wheel	AISI M2, D2 and H11	X	X		X	X

Table 7, Summary of the studies on the cryogenic machining of stainless steel workpiece materials (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperatures)

Author	Cryogen	Operation	Tool	Workpiece	Area of Study			
					S	F	L	T
Nalbant and Yildiz 2011	LN ₂	Milling	Uncoated WC	AISI 304		X	X	
Rozzi et al. 2011	LN ₂	Turning	Uncoated WC	AISI 416			X	X
Khan et al. 2010	LN ₂	Turning	Coated WC	AISI 304	X		X	
Kalyankumar and Choudhury 2008	LN ₂	Turning	PVD TiN coated WC	AISI 202		X	X	
Khan and Ahmed 2008	LN ₂	Turning	TiCN coated WC	AISI 304			X	
De Chiffre et al. 2007	CO ₂ +MQL	Turning	Coated WC	AISI 304 and 316	X	X	X	
Benfredj et al. 2006	LN ₂	Grinding	99A46M7V10N	AISI 304	X	X		X
Benfredj and Sidhom 2006	LN ₂	Grinding	99A60M7V10N	AISI 304	X			
Ostrovskaya et al. 2001	LN ₂	Sliding	Different Coatings	AISI 304				
Hong and Broomer 2000	LN ₂	Turning	TiN coated WC	AISI 304			X	
Evans and Bryan 1991	LN ₂	Turning	PCD	AISI 304	X		X	
Uehara and Kumagai 1970	LN ₂	Turning	HSS	AISI 304	X	X	X	X
Uehara and Kumagai 1968	LN ₂	Turning	HSS	AISI 304	X	X	X	X

In comparison with steels, machining titanium alloys is very critical. This is due to the chemical affinity of titanium to all known cutting tool materials together with high cutting zone temperatures, high material strength and poor thermal conductivity (Shokrani et al. 2012b). These characteristics have resulted in poor machinability of the material together with high machining costs and low productivity. As a result, industry tends to use more advanced cutting tools to increase productivity and reduce the tool change costs as the main

application of titanium alloys is for components used in aerospace and gas turbine industries with high buy-to-fly ratios resulting in substantial machining costs (Sun et al. 2010).

Despite the advantages of cryogenic cooling in machining titanium alloys, as shown in table 8 there is very limited research on different cryogenic cutting operations. For instance, while 22.4% of the research in cryogenic machining has focused on titanium alloys, only 18% of the studies in cryogenic milling and 13% of the investigations in cryogenic machining of titanium alloys are related to cryogenic milling of titanium. In addition, there is no report on the cryogenic drilling of this material.

Nickel alloys with mechanical and thermal properties superior to titanium alloys is another machining challenge for manufacturing industries. Similar to studies on machining titanium alloys, most researchers have (table 9) stated that cryogenic cooling enhances the machinability of nickel alloys and reduces machining cost significantly. However, only 6.5% of the studies on cryogenic machining have concentrated on machining nickel alloys with only two experiment on the milling of Udimet 720 (Truesdale and Shin 2009) and Inconel® 718 (Shokrani et al. 2012a). Truesdale and Shin (2009) reported that while cryogenic cooling of the workpiece reduced the tool life, increased productivity can reduce total machining cost by up to 90%. Thus, there is a significant further area of study on the effects of cryogenic cooling on the machinability and machining cost of nickel alloys.

There are a very limited number of studies on cryogenic machining of other materials such as tantalum, cobalt-chrome alloys, polymers, WC-Co composites, aluminium alloys and structural ceramics. The most significant studies among these are cryogenic milling and micro milling of the polymers which are shown in the table 10.

Table 8, Summary of the studies on the cryogenic machining of titanium alloys (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperatures)

Author	Cryogen	Operation	Cutting Tool	Workpiece	Areas of Study			
					S	F	L	T
Dhokia et al. 2012a	LN ₂	End milling	TiAlN WC	Ti-6Al-4V	X		X	
Klocke et al. 2012	LN ₂	Turning	WC	Ti-6Al-4V			X	
Shokrani et al. 2012c	LN ₂	End milling	Uncoated WC	Ti-6Al-4V	X			
Shokrani et al. 2012d	LN ₂	End milling	TiAlN coated WC	Ti-6Al-4V	X		X	
Birmingham et al. 2011a	LN ₂	Turning	Uncoated WC	Ti-6Al-4V			X	
Birmingham et al. 2011b	LN ₂	Turning	Uncoated WC	Ti-6Al-4V		X	X	
Dhananchezian and Kumar 2011	LN ₂	Turning	TiAlN coated WC	Ti-6Al-4V	X	X	X	X
Machai and Biermann 2011	LN ₂	Turning	(Ti-Al)N-TiN coated WC	Ti-10V-2Fe-3Al		X	X	
Yuan et al. 2011	Air -45	Turning	Uncoated WC	Ti-6Al-4V	X	X	X	
Dandekar et al. 2010	LN ₂	Laser assisted turning	Different coated WC	Ti-6Al-4V	X	X	X	
El-Tayeb et al. 2010, 2009	LN ₂	Sliding	Uncoated WC	Ti-5Al-4V				
El-Tayeb et al. 2010, 2009	LN ₂	Sliding	Uncoated WC	Ti-6Al-4V				
Sun et al. 2010	cryogenically cooled air	Turning	Uncoated WC	Ti-6Al-4V		X	X	X
Ke et al. 2009	LN ₂	High speed milling	TiAlN coated WC	Ti-6Al-4V	X	X	X	
Pusavec and Kopac 2009	LN ₂	Turning		Ti-6Al-4V			X	
Venugopal et al. 2007a	LN ₂	Turning	Uncoated WC	Ti-6Al-4V			X	
Venugopal et al. 2007b	LN ₂	Turning	Uncoated WC	Ti-6Al-4V			X	
Paul and Chattopadhyay 2006	LN ₂	Turning	Uncoated WC	Ti-6Al-4V			X	
Venugopal et al. 2003	LN ₂	Turning	TiB ₂ coated WC	Ti-5Al-5Mo-2Sn-V	X	X	X	X
Hong et al. 2002	LN ₂	Sliding	Uncoated WC	Ti-6Al-4V				
Hong et al. 2002	LN ₂	Sliding	TiC-TiN-TiCN coated WC	Ti-6Al-4V				
Hong and Ding 2001a	LN ₂	Turning	Uncoated WC	Ti-6Al-4V				X
Hong et al. 2001a	LN ₂	Turning	Uncoated WC	Ti-6Al-4V		X		
Hong et al. 2001b	LN ₂	Turning	Uncoated WC	Ti-6Al-4V			X	X
Wang and Rajurkar 2000	LN ₂	Turning	Uncoated WC	Ti-6Al-4V	X		X	
Uehara and Kumagai 1970	LN ₂	Turning	HSS	99.99% pure titanium	X	X	X	X
Uehara and Kumagai 1968	LN ₂	Turning	HSS	99.99% pure titanium	X	X	X	X

Table 9, Summary of studies on the effects of cryogenic machining on the machinability of nickel alloys (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperatures)

Author	Cryogen	Operation	Tool	Workpiece	Area of Study			
					S	F	L	T
Shokrani et al. 2012a	LN ₂	End milling	TiAlN coated WC	Inconel® 718	X		X	
Kenda et al. 2011	LN ₂	Turning	Coated WC	Inconel® 718	X			
Pusavec et al. 2011	LN ₂	Turning	Uncoated WC	Inconel® 718	X	X		
Pusavec et al. 2010	LN ₂	Turning	TiAlN Coated WC	Inconel® 718			X	
Kopac 2009	MQL+LN ₂	Turning	Uncoated WC	Inconel® 718	X		X	X
Truesdale and Shin 2009	LN ₂	Face milling	Sn-TiN coated Carbide	Udimet® 720	X	X	X	
Su et al. 2007	MQL+ Chilled Air	Turning	TiAlN Coated WC	Inconel® 718	X		X	
Wang et al. 2003	Plasma+ LN ₂	Turning	PCBN	Inconel® 718	X	X	X	
Wang and Rajurkar 2000	LN ₂	Turning	PCBN	Inconel® 718	X		X	

Table 10, Summary of the studies on the cryogenic machining of polymeric materials

Author	Cryogen	Operation	Tool	Workpiece
Kakinuma et al. 2012	LN ₂	Micro Milling	WC	poly-dimethyl-siloxane (PDMS)
Dhokia et al. 2010	LN ₂	Milling	Uncoated WC	ethylene-vinyl acetate (EVA)
Mishima et al. 2010	LN ₂	Micro Milling	WC	poly-dimethyl-siloxane (PDMS)
Kakinuma et al. 2008	LN ₂	Micro Milling	Uncoated WC	poly-dimethyl-siloxane (PDMS)
Shih et al. 2004a	CO ₂ Dry Ice	End milling	Wood working router bits	elastomer
Shih et al. 2004b	CO ₂ Dry Ice	End milling	Wood working router bits	elastomer
Friedrich 2000	LN ₂	Micro Milling	HSS	Polymethyl methacrylate (PMMA)

Cryogenic milling of polymers is defined as the most suitable method for machining personalised or modified products and prototypes as an alternative to expensive and time consuming processes such as moulding, micro-moulding and photolithography. Despite successful application of cryogenic milling of polymers, the research in this area is very limited and all papers are published after the year 2000. It is noteworthy to mention that the optimal cutting parameters in this technique are still unclear and the workpiece materials are very restricted. This is a significant research area related to defining the optimal cutting parameters and their effects on the machinability of different polymer materials.

From the cutting tool material point of view, as illustrated in figure 10, 68% of the cutting tools used in cryogenic machining studies are WC. Almost one third of these were coated carbide tools with different coatings and coating methods namely, PVD and PCD. Based on the review in the section 3.4.3 most of the studies stated that cryogenic cooling resulted in longer tool life when machining different materials. Though, while carbide tools are significantly cheaper than more advanced tools such as CBN, PCBN, PCD, SCD etc., there are limited studies on comparative cost implications of using cheaper options in cryogenic machining compared to advanced cutting tools in conventional environments.

4 Conclusion:

This paper reviewed the application of cryogenics in machining processes. In general, cryogenics in machining operations was classified into two categories of (i) cryogenic processing and (ii) cryogenic machining. Cryogenic processing was identified as an extended heat treatment process in a typical heat treatment cycle. Most studies in this area are concentrated on the cryo-processing of HSS cutting tools and also carbide tools. Different theories to explain the effects of cryo-processing on the material structure of the cutting tool materials were identified and are listed below:

- Austenite transformation
- Carbide precipitation
- Formation of the μ phase in the material microstructure

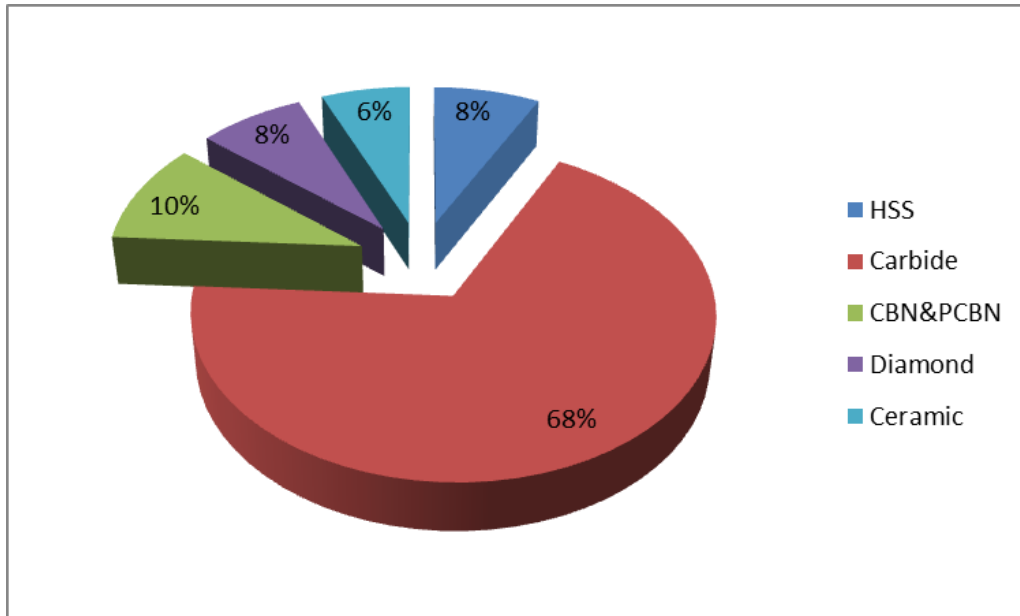


Figure 10, Distribution of the cutting tool materials used in the studies in cryogenic machining

Nevertheless, none of the above theories can completely explain the changes in performance of the treated tools and further research is required.

In cryogenic machining, a cryogen is used to cool the workpiece material and/or cutting tool during the cutting operation. The cooling technique is highly dependent on the workpiece-tool materials. For instance, while workpiece cooling is suggested for ductile materials, cooling the cutting zone or cutting tool is recommended more for harder materials. In majority of cases, researchers have reported that cryogenic cooling has positively impacted on the machinability of different materials in terms of tool life and surface finish. Though, as mentioned in section 3.6.2, most studies in cryogenic machining have concentrated on turning operations for steel and titanium alloys. Hence, the authors conclude that further research in

cryogenic machining using other machining operations such as milling and drilling with different tool-workpiece materials is essential.

References:

- Abele, E. and Fröhlich, B. 2008. High speed milling of titanium alloys. *Advances in Production Engineering & Management*, 3, 1.
- Abele, E. and Schramm, B. 2008. Using PCD for machining CGI with a CO₂ coolant system. *Production Engineering*, 2(2), 165-169.
- Aggarwal, A., et al. 2008a. Optimization of multiple quality characteristics for CNC turning under cryogenic cutting environment using desirability function. *Journal of Materials Processing Technology*, 205(1-3), 42-50.
- Aggarwal, A., et al. 2008b. Optimizing power consumption for CNC turned parts using response surface methodology and Taguchi's technique—A comparative analysis. *Journal of Materials Processing Technology*, 200(1-3), 373-384.
- Aggarwal, A., et al. 2009. Optimizing feed and radial forces in CNC machining of P-20 tool steel through Taguchi's parameter design approach. *Indian Journal of Engineering & Materials Sciences*, 16, 23-32.
- Ahmed, M., et al. 2007. Effectiveness of cryogenic machining with modified tool holder. *Journal of Materials Processing Technology*, 185(1-3), 91-96.
- Air Products, 2011. *ICEFLY® Cryogen Delivery System* [online]. Allentown, PA. Available from: <http://airproducts.com/en/company/technology-partnerships/technology-licensing/gases/gases-icefly-cryogen-delivery-system.aspx> [Accessed 6 Jan 2012].
- Arunachalam, R. and Mannan, M. 2000. Machinability of nickel-based high temperature alloys. *Machining Science and Technology*, 4(1), 127-168.
- Astakhov, V. P., 2006. *Tribology of Metal Cutting*. Rochester Hills, Michigan: Elsevier Science.
- Axer, H. 1954. Zur Physik des Werkzeugverschleisses. In: *Shaw, M.C. and Smith, P.A, 1956. Methods of applying cutting fluids. American Society of Tool and Manufacturing Engineers, paper no. RR-3.*
- Benfredj, N. and Sidhom, H. 2006. Effects of the cryogenic cooling on the fatigue strength of the AISI 304 stainless steel ground components. *Cryogenics*, 46(6), 439-448.
- Benfredj, N., Sidhom, H. and Braham, C. 2006. Ground surface improvement of the austenitic stainless steel AISI 304 using cryogenic cooling. *Surface and Coatings Technology*, 200(16-17), 4846-4860.
- Birmingham, M., et al. 2011a. A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti-6Al-4V cutting. *Journal of Materials Processing Technology*.
- Birmingham, M. J., et al. 2011b. New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. *International Journal of Machine Tools and Manufacture*, 51(6), 500-511.
- Bhattacharyya, D. and Horrigan, D. 1998. A study of hole drilling in Kevlar composites. *Composites science and technology*, 58(2), 267-283.
- Biermann, D. and Heilmann, M. 2010. Improvement of workpiece quality in face milling of aluminum alloys. *Journal of Materials Processing Technology*, 210(14), 1968-1975.
- Brinksmeier, E. and Glabe, R. 2001. Advances in precision machining of steel. *CIRP Annals - Manufacturing Technology*, 50(1), 385-388.
- Busch, W. S. 1969. Introduction to cryogenics. *ASTME Technical Paper, CM69-252*.
- Dandekar, C. R., Shin, Y. C. and Barnes, J. 2010. Machinability improvement of titanium alloy (Ti-6Al-4V) via LAM and hybrid machining. *International Journal of Machine Tools and Manufacture*, 50(2), 174-182.

- Das, D., *et al.* 2007. Effect of deep cryogenic treatment on the carbide precipitation and tribological behavior of D2 steel. *Materials and Manufacturing Processes*, 22(4), 474 - 480.
- Dasilva, F., *et al.* 2006. Performance of cryogenically treated HSS tools. *Wear*, 261(5-6), 674-685.
- Davim, J. P. 2002. Diamond tool performance in machining metal-matrix composites. *Journal of Materials Processing Technology*, 128(1-3), 100-105.
- De Chiffre, L., *et al.* 2007. Performance testing of cryogenic CO₂ as cutting fluid in parting/grooving and threading austenitic stainless steel. *CIRP Annals - Manufacturing Technology*, 56(1), 101-104.
- Dhananchezian, M. and Kumar, M. P. 2011. Cryogenic turning of the Ti-6Al-4V alloy with modified cutting tool inserts. *Cryogenics*, 51(1), 34-40.
- Dhananchezian, M., Kumar, M. P. and Rajaduari, A. 2009. Experimental investigation of cryogenic cooling by liquid nitrogen in the orthogonal machining process. *International Journal of Recent Trend in Engineering*, 1(5), 55-59.
- Dhar, N., *et al.* 2006a. The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. *Journal of Materials Processing Technology*, 171(1), 93-99.
- Dhar, N. and Kamruzzaman, M. 2007. Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition. *International Journal of Machine Tools and Manufacture*, 47(5), 754-759.
- Dhar, N., *et al.* 2002a. The effects of cryogenic cooling on chips and cutting forces in turning AISI 1040 and AISI 4320 steels. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 216(5), 713-724.
- Dhar, N. R., *et al.* 2006b. Wear behavior of uncoated carbide inserts under dry, wet and cryogenic cooling conditions in turning C-60 steel. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 28, 146-152.
- Dhar, N. R., Paul, S. and Chattopadhyay, A. B. 2002b. The influence of cryogenic cooling on tool wear, dimensional accuracy and surface finish in turning AISI 1040 and E4340C steels. *Wear*, 249(10-11), 932-942.
- Dhar, N. R., Paul, S. and Chattopadhyay, A. B. 2002c. Machining of AISI 4140 steel under cryogenic cooling--tool wear, surface roughness and dimensional deviation. *Journal of Materials Processing Technology*, 123(3), 483-489.
- Dhar, N. R., Paul, S. and Chattopadhyay, A. B. 2002d. Role of cryogenic cooling on cutting temperature in turning steel. *Journal of Manufacturing Science and Engineering*, 124(1), 146.
- Dhokia, V., Shokrani, A. and Newman, S. T., 2012a. Study of cryogenics in CNC milling of metal Alloys (Keynote). *International Chemnitz Manufacturing Colloquium in association with the 2nd International Colloquium of the Cluster of Excellenz eniPROD*. Chemnitz.
- Dhokia, V., *et al.*, 2012b. Cryogenic machining of carbon fibre. *12th European Society for Precision Engineering and Nanotechnology (euspen 2012) International Conference*. Stockholm.
- Dhokia, V. G., 2009. *The Cryogenic sculpture surface machining of elastomers*. (PhD). University of Bath.
- Dhokia, V. G., *et al.* 2010. A methodology for the determination of foamed polymer contraction rates as a result of cryogenic CNC machining. *Robotics and Computer-Integrated Manufacturing*, 26(6), 665-670.

- Dutra Xavier, S. E., Delijaicov, S. and de Farias, A., Investigation on the surface integrity and tool wear in cryogenic machining. *International Conference on Advances in Material and Processing Technologies*, 2011, 1199-1204.
- Edwards, T. 2003. Liquid fuels and propellants for aerospace propulsion: 1903-2003. *Journal of Propulsion and Power*, 19(6), 1089-1107.
- El-Gallab, M. and Sklad, M. 1998. Machining of Al/SiC particulate metal-matrix composites: Part I: Tool performance. *Journal of Materials Processing Technology*, 83(1-3), 151-158.
- El-Tayeb, N. S. M., Yap, T. C. and Brevern, P. V. 2010. Wear characteristics of titanium alloy Ti54 for cryogenic sliding applications. *Tribology International*, 43(12), 2345-2354.
- El-Tayeb, N. S. M., *et al.* 2009. Modeling of cryogenic frictional behaviour of titanium alloys using Response Surface Methodology approach. *Materials & Design*, 30(10), 4023-4034.
- Evans, C. and Bryan, J. B. 1991. Cryogenic diamond turning of stainless steel. *CIRP Annals - Manufacturing Technology*, 40(1), 571-575.
- Firouzdor, V., Nejati, E. and Khomamizadeh, F. 2008. Effect of deep cryogenic treatment on wear resistance and tool life of M2 HSS drill. *Journal of Materials Processing Technology*, 206(1-3), 467-472.
- Friedrich, C. 2000. Near-cryogenic machining of polymethyl methacrylate for micromilling tool development. *Materials and Manufacturing Processes*, 15(5), 667-678.
- Ghosh, R., Zurecki, Z. and Frey, J. H., Cryogenic machining with brittle tools and effects on tool life. *Proceedings of ASME International Mechanical Engineering Congress and Exposition*, 2003 Washington, D.C.
- Gill, S. S., *et al.* 2009. Cryoprocessing of cutting tool materials—a review. *The International Journal of Advanced Manufacturing Technology*, 48(1-4), 175-192.
- Gill, S. S., *et al.* 2011. Metallurgical principles of cryogenically treated tool steels—a review on the current state of science. *The International Journal of Advanced Manufacturing Technology*, 54, 59-82.
- Gulyaev, A. 1937. Improved methods of heat treating high speed steels to improve the cutting properties. *Metallurgy*, 12, 65-77.
- Harris, D. 1970. Another big step forward in modern metalworking. *Society of Manufacturing Engineers*, TECH Paper No. AD70-734, 4 P.
- Hong, H., *et al.* 1993. Machinability of steels and titanium alloys under lubrication. *Wear*, 162–164, Part A(0), 34-39.
- Hong, S. 2006. Lubrication mechanisms of LN2 in ecological cryogenic machining. *Machining Science and Technology*, 10(1), 133-155.
- Hong, S., Ding, Y. and Jeong, J. 2002. Experimental evaluation of friction coefficient and liquid nitrogen lubrication effect in cryogenic machining. *Machining Science and Technology*, 6(2), 235-250.
- Hong, S. Y., 1999. *Cryogenic machining*. US application 5,901,623, May 11, 1999.
- Hong, S. Y. and Broomer, M. 2000. Economical and ecological cryogenic machining of AISI 304 austenitic stainless steel. *Clean Technologies and Environmental Policy*, 2(3), 157-166.
- Hong, S. Y. and Ding, Y. 2001a. Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V. *International Journal of Machine Tools and Manufacture*, 41(10), 1417-1437.
- Hong, S. Y. and Ding, Y. 2001b. Micro-temperature manipulation in cryogenic machining of low carbon steel. *Journal of Materials Processing Technology*, 116(1), 22-30.

- Hong, S. Y., Ding, Y. and Ekkens, R. G. 1999. Improving low carbon steel chip breakability by cryogenic chip cooling. *International Journal of Machine Tools and Manufacture*, 39(7), 1065-1085.
- Hong, S. Y., Ding, Y. and Jeong, W. 2001a. Friction and cutting forces in cryogenic machining of Ti-6Al-4V. *International Journal of Machine Tools and Manufacture*, 41(15), 2271-2285.
- Hong, S. Y., Markus, I. and Jeong, W. 2001b. New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V. *International Journal of Machine Tools and Manufacture*, 41(15), 2245-2260.
- Hong, S. Y. and Zhao, Z. 1999. Thermal aspects, material considerations and cooling strategies in cryogenic machining. *Clean Technologies and Environmental Policy*, 1(2), 107-116.
- Hübner, W., *et al.* 1998. Tribological behaviour of materials at cryogenic temperatures. *Wear*, 216(2), 150-159.
- Jainbajranglal, J. R. and Chattopadhyay, A. 1984. Role of cryogenics in metal cutting industry. *Indian Journal of Cryogenics*, 9(1), 42-46.
- Jawahir, I., *et al.* 2011. Surface integrity in material removal processes: Recent advances. *CIRP Annals-Manufacturing Technology*.
- Jen, T., *et al.* 2002. Investigation of heat pipe cooling in drilling applications.: part I: preliminary numerical analysis and verification. *International Journal of Machine Tools and Manufacture*, 42(5), 643-652.
- Jun, S. C. 2005. Lubrication effect of liquid nitrogen in cryogenic machining friction on the tool-chip interface. *Journal of Mechanical Science and Technology*, 19(4), 936-946.
- Kakinuma, Y., Kidani, S. and Aoyama, T. 2012. Ultra-precision cryogenic machining of viscoelastic polymers. *CIRP Annals - Manufacturing Technology*, 61(1), 79-82.
- Kakinuma, Y., Yasuda, N. and Aoyama, T. 2008. Micromachining of soft polymer material applying cryogenic cooling. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, 2(4), 560-569.
- Kalia, S. 2009. Cryogenic processing: A study of materials at low temperatures. *Journal of Low Temperature Physics*, 158(5-6), 934-945.
- Kalyankumar, K. and Choudhury, S. 2008. Investigation of tool wear and cutting force in cryogenic machining using design of experiments. *Journal of Materials Processing Technology*, 203(1-3), 95-101.
- Kamody, D. J. 1999. Cryogenics process update. *Advanced Materials & Processes*, 155(6), H67-H69.
- Karassik, I. J., *et al.*, 2008. Pump handbook (4th Edition). McGraw-Hill.
- Ke, Y.-l., *et al.* 2009. Use of nitrogen gas in high-speed milling of Ti-6Al-4V. *Transactions of Nonferrous Metals Society of China*, 19(3), 530-534.
- Kenda, J., Pusavec, F. and Kopac, J. 2011. Analysis of residual stresses in sustainable cryogenic machining of nickel based alloy—Inconel 718. *Journal of Manufacturing Science and Engineering*, 133, 041009-041007.
- Khan, A. and Ahmed, M. 2008. Improving tool life using cryogenic cooling. *Journal of Materials Processing Technology*, 196(1-3), 149-154.
- Khan, A. A., Ali, M. Y. and Haque, M. 2010. A new approach of applying cryogenic coolant in turning AISI 304 stainless steel. *International Journal of Mechanical and Materials Engineering (IJMME)*, 5(2), 171-174.
- Kitagawa, T., Kubo, A. and Maekawa, K. 1997. Temperature and wear of cutting tools in high-speed machining of Inconel 718 and Ti-6Al-6V-2Sn. *Wear*, 202(2), 142-148.

- Klocke, F., *et al.*, Thermo-mechanical tool load during high performance cutting of hard-to-cut materials. *5th CIRP Conference on High Performance Cutting*, 2012 Zürich, 312-317.
- Kopac, J. 2009. Achievements of sustainable manufacturing by machining. *Manufacturing Engineering*, 34(2), 180-187.
- Leskovsek, V., Kalin, M. and Vizintin, J. 2006. Influence of deep-cryogenic treatment on wear resistance of vacuum heat-treated HSS. *Vacuum*, 80(6), 507-518.
- Lin, C., *et al.* 2001. Machining and fluidity of 356Al/SiC (p) composites. *Journal of Materials Processing Technology*, 110(2), 152-159.
- Liu, J. and Kevinchou, Y. 2007. On temperatures and tool wear in machining hypereutectic Al–Si alloys with vortex-tube cooling. *International Journal of Machine Tools and Manufacture*, 47(3-4), 635-645.
- Machai, C. and Biermann, D. 2011. Machining of β -titanium-alloy Ti–10V–2Fe–3Al under cryogenic conditions: Cooling with carbon dioxide snow. *Journal of Materials Processing Technology*.
- MAG, 2012. *Cryogenics* [online]. New York. Available from: <http://www.mag-ias.com/en/mag/technologies/cryogenics.html> [Accessed 15 January 2012].
- Marquardt, E., Le, J. and Radebaugh, R. 2002. Cryogenic material properties database. *Cryocoolers 11*, 681-687.
- Mishima, K., Kakinuma, Y. and Aoyama, T. 2010. Pre-deformation-assisted cryogenic micromachining for fabrication of three-dimensional unique micro channels. *Journal of Advanced Mechanical Design, Systems and Manufacturing*, 4(5), 936-947.
- Molinari, A., *et al.* 2001. Effect of deep cryogenic treatment on the mechanical properties of tool steels. *Journal of Materials Processing Technology*, 118(1-3), 350-355.
- Murthy, J. K. N., Chattopadhyay, A. B. and Chakrabarti, A. K. 2000. Studies on the grindability of some alloy steels. *Journal of Materials Processing Technology*, 104(1-2), 59-66.
- Nalbant, M. and Yildiz, Y. 2011. Effect of cryogenic cooling in milling process of AISI 304 stainless steel. *Transactions of Nonferrous Metals Society of China*, 21(1), 72-79.
- NISA, 2011. *NISA* [online]. Troy, MI: Cranes Software International Limited. Available from: <http://nisasoftware.com> [Accessed 13 Oct 2011].
- Noorul Haq, A. and Tamizharasan, T. 2005. Investigation of the effects of cooling in hard turning operations. *The International Journal of Advanced Manufacturing Technology*, 30(9-10), 808-816.
- Ostrovskaya, Y. L., *et al.* 2001. Friction and wear behaviour of hard and superhard coatings at cryogenic temperatures. *Tribology International*, 34(4), 255-263.
- Pahlitzsch, G. 1953. Gases are good cutting coolants, *American Machinist* 97(1953), 196.
- Paul, S. and Chattopadhyay, A. 1995. Effects of cryogenic cooling by liquid nitrogen jet on forces, temperature and surface residual stresses in grinding steels. *Cryogenics*, 35(8), 515-523.
- Paul, S. and Chattopadhyay, A. 1996a. Determination and control of grinding zone temperature under cryogenic cooling. *International Journal of Machine Tools and Manufacture*, 36(4), 491-501.
- Paul, S. and Chattopadhyay, A. 1996b. The effect of cryogenic cooling on grinding forces. *International Journal of Machine Tools and Manufacture*, 36(1), 63-72.
- Paul, S. and Chattopadhyay, A. B. 2006. Environmentally conscious machining and grinding with cryogenic cooling. *Machining Science and Technology*, 10(1), 87-131.

- Paul, S., Dhar, N. and Chattopadhyay, A. 2001. Beneficial effects of cryogenic cooling over dry and wet machining on tool wear and surface finish in turning AISI 1060 steel. *Journal of Materials Processing Technology*, 116(1), 44-48.
- Preciado, M., Bravo, P. M. and Alegre, J. M. 2006. Effect of low temperature tempering prior cryogenic treatment on carburized steels. *Journal of Materials Processing Technology*, 176(1-3), 41-44.
- Pu, Z., *et al.* 2011a. Analysis of surface integrity in dry and cryogenic machining of AZ31B Mg alloy. *Advanced Material Research*, 223, 439-448.
- Pu, Z., *et al.*, Microstructural changes of AZ31 magnesium alloys induced by cryogenic machining and its influence on corrosion resistance in simulated body fluid for biomedical applications. *Proceedings of the 2010 ASME Int MSEC*, 2010.
- Pu, Z., *et al.*, Controlling the biodegradation rate of magnesium-based implants through surface nanocrystallization induced by cryogenic machining. *Proceeding of Magnesium Technology*, 2011b.
- Pu, Z., *et al.* 2011c. Ultrafine-grained surface layer on Mg-Al-Zn alloy produced by cryogenic burnishing for enhanced corrosion resistance. *Scripta Materialia*, 65, 520-523.
- Pusavec, F. 2012. Porous tungsten machining under cryogenic conditions. *International Journal of Refractory Metals and Hard Materials*, (In Press), (0).
- Pusavec, F., *et al.* 2011. Surface integrity in cryogenic machining of nickel based alloy—Inconel 718. *Journal of Materials Processing Technology*, 211(4), 773-783.
- Pusavec, F. and Kopac, J. 2009. Achieving and implementation of sustainability principles in machining processes. *Journal of Advances in Production Engineering and Management*, 3-4, 58-69.
- Pusavec, F., *et al.* 2010. Transitioning to sustainable production – part II: evaluation of sustainable machining technologies. *Journal of Cleaner Production*, 18(12), 1211-1221.
- Rahman, M., *et al.* 2003. Effect of chilled air on machining performance in end milling. *The International Journal of Advanced Manufacturing Technology*, 21(10), 787-795.
- Ramji, B. R., *et al.* 2010. Performance study of cryogenically treated HSS drills in drilling gray cast iron using orthogonal array technique. *Research Journal of Applied Sciences, Engineering and Technology*, 2(5), 487-491.
- Ravi, S. and Kumar, M. P. 2011. Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel. *Cryogenics*, 51(9), 509-515.
- Rozzi, J. C., Sanders, J. K. and Chen, W. 2011. The Experimental and theoretical evaluation of an indirect cooling system for machining. *Journal of Heat Transfer*, 133(3), 031006.
- Schulz, H. and Moriwaki, T. 1992. High-speed machining. *CIRP Annals - Manufacturing Technology*, 41(2), 637-643.
- Seah, K. H. W., Rahman, M. and Yong, K. H. 2003. Performance evaluation of cryogenically treated tungsten carbide cutting tool inserts. *Proceedings of the Institution of Mechanical Engineers- Part B Journal of Engineering Manufacture*, 217(1), 29-43.
- Shaw, M.C. and Smith, P.A, 1956. Methods of applying cutting fluids. *American Society of Tool and Manufacturing Engineers (ASTME)*, paper no. RR-3.
- Shih, A. J., Lewis, M. A. and Strenkowski, J. S. 2004a. End milling of elastomers—fixture design and tool effectiveness for material removal. *Journal of Manufacturing Science and Engineering*, 126(1), 115-123.
- Shih, A. J., *et al.* 2004b. Chip Morphology and Forces in End Milling of Elastomers. *Journal of Manufacturing Science and Engineering*, 126(1), 124-130.

- Shokrani, A., *et al.*, 2012a. An initial study of the effect of using liquid nitrogen coolant on the surface roughness of Inconel 718 nickel-based alloy in CNC milling. *45th CIRP Conference on Manufacturing Systems*. Athenes.
- Shokrani, A., Dhokia, V. and Newman, S. T. 2012b. Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids. *International Journal of Machine Tools and Manufacture*, 57, 83-101.
- Shokrani, A., Dhokia, V. and Newman, S. T., 2012c. Evaluation of cryogenic CNC milling of Ti-6Al-4V titanium alloy. *22nd International Conference on Flexible Automation and Intelligent Manufacturing*. Helsinki-Stockholm.
- Shokrani, A., Dhokia, V. and Newman, S. T., 2012d. Study of the effects of cryogenic machining on the machinability of Ti-6Al-4V titanium alloy. *12th European Society for Precision Engineering and Nanotechnology (euspen 2012) International Conference*. Stockholm.
- Sreeramareddy, T., *et al.* 2009. Machinability of C45 steel with deep cryogenic treated tungsten carbide cutting tool inserts. *International Journal of Refractory Metals and Hard Materials*, 27(1), 181-185.
- Stewart, H. A. 2004. Cryogenic treatment of tungsten carbide reduces tool wear when machining medium density fiberboard. *Forest products journal*, 54(2), 53-56.
- Su, Y., *et al.* 2007. Refrigerated cooling air cutting of difficult-to-cut materials. *International Journal of Machine Tools and Manufacture*, 47(6), 927-933.
- Sun, S., Brandt, M. and Dargusch, M. S. 2010. Machining Ti-6Al-4V alloy with cryogenic compressed air cooling. *International Journal of Machine Tools and Manufacture*, 50(11), 933-942.
- Tanaka, T. and Akasawa, T. 1999. Machinability of hypereutectic silicon-aluminum alloys. *Journal of Materials Engineering and Performance*, 8(4), 463-468.
- Tarter, J. O., *et al.*, Cryogenic machining of porous tungsten for dispenser cathode applications. *Vacuum Electronics Conference, 2008. IVEC 2008. IEEE International*, 2008, 293-294.
- Taylor, F. W., 1907. *On the art of cutting metals*. New York: American Society of Mechanical Engineers.
- Thiele, J. D. and Melkote, S. N. 1999. Effect of cutting edge geometry and workpiece hardness on surface generation in the finish hard turning of AISI 52100 steel. *Journal of Materials Processing Technology*, 94(2-3), 216-226.
- Timmerhaus, K. D. and Reed, R. P., 2007. *Cryogenic engineering: fifty years of progress*. Springer Verlag.
- Trent, E. M. and Wright, P. K., 2000. *Metal Cutting*. Oxford: Butterworth-Heinemann.
- Truesdale, S. and Shin, Y. 2009. Microstructural analysis and machinability improvement of Udimet 720 via cryogenic milling. *Machining Science and Technology*, 13(1), 1-19.
- Tsai, H. and Hocheng, H. 1998. Investigation of the transient thermal deflection and stresses of the workpiece in surface grinding with the application of a cryogenic magnetic chuck. *Journal of Materials Processing Technology*, 79(1-3), 177-184.
- Uehara, K. and Kumagai, S. 1968. Chip formation, surface roughness and cutting force in cryogenic machining. *Annals of CIRP*, 17(1), 409-416.
- Uehara, K. and Kumagai, S. 1970. Characteristics of tool wear in cryogenic machining. *Annals of CIRP*, 18, 273-277.
- Ulutun, D. and Ozel, T. 2011. Machining induced surface integrity in titanium and nickel alloys: A review. *International Journal of Machine Tools and Manufacture*, 51(3), 250-280.

- Umbrello, D., *et al.*, The effect of cryogenic cooling on white layer formation in hard machining. *Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition*, 2011 Colorado, USA.
- Umbrello, D., Micari, F. and Jawahir, I. S. 2012. The effects of cryogenic cooling on surface integrity in hard machining: A comparison with dry machining. *CIRP Annals - Manufacturing Technology*, 61(1), 103-106.
- Venugopal, K., Paul, S. and Chattopadhyay, A. 2007a. Growth of tool wear in turning of Ti-6Al-4V alloy under cryogenic cooling. *Wear*, 262(9-10), 1071-1078.
- Venugopal, K., Paul, S. and Chattopadhyay, A. 2007b. Tool wear in cryogenic turning of Ti-6Al-4V alloy. *Cryogenics*, 47(1), 12-18.
- Venugopal, K., *et al.* 2003. Turning of titanium alloy with TiB₂-coated carbides under cryogenic cooling. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 217(12), 1697-1707.
- Wang, Z. 2005. High-speed milling of titanium alloys using binderless CBN tools. *International Journal of Machine Tools and Manufacture*, 45(1), 105-114.
- Wang, Z. and Rajurkar, K. 1997. Wear of CBN tool in turning of silicon nitride with cryogenic cooling. *International Journal of Machine Tools and Manufacture*, 37(3), 319-326.
- Wang, Z. and Rajurkar, K. 2000. Cryogenic machining of hard-to-cut materials. *Wear*, 239(2), 168-175.
- Wang, Z., *et al.* 2002. Cryogenic machining of Tantalum. *Journal of Manufacturing Processes*, 4(2), 122-127.
- Wang, Z., Rajurkar, K. and Murugappan, M. 1996. Cryogenic PCBN turning of ceramic (Si₃N₄). *Wear*, 195(1-2), 1-6.
- Wang, Z. Y., *et al.* 2003. Hybrid machining of Inconel 718. *International Journal of Machine Tools and Manufacture*, 43(13), 1391-1396.
- Yalcin, B., Ozgur, A. and Koru, M. 2009. The effects of various cooling strategies on surface roughness and tool wear during soft materials milling. *Materials & Design*, 30(3), 896-899.
- Yang, S., *et al.*, 2011. Cryogenic Processing of Biomaterials for Improved Surface Integrity and Product Sustainability. In: Seliger, G., Khraisheh, M. M. K. and Jawahir, I. S. eds. *Advances in Sustainable Manufacturing*. Springer Berlin Heidelberg, 177-182.
- Yildiz, Y. and Nalbant, M. 2008. A review of cryogenic cooling in machining processes. *International Journal of Machine Tools and Manufacture*, 48(9), 947-964.
- Yong, A. Y. L., Seah, K. H. W. and Rahman, M. 2006. Performance of cryogenically treated tungsten carbide tools in milling operations. *The International Journal of Advanced Manufacturing Technology*, 32(7-8), 638-643.
- Yuan, S. M., *et al.* 2011. Effects of cooling air temperature on cryogenic machining of Ti-6Al-4V alloy. *Journal of Materials Processing Technology*, 211(3), 356-362.
- Zhao, Z. and Hong, S. 1992. Cooling strategies for cryogenic machining from a materials viewpoint. *Journal of Materials Engineering and Performance*, 1(5), 669-678.
- Zurecki, Z., Ghosh, R. and Frey, J. H., Investigation of white layers formed in conventional and cryogenic hard turning of steels. *Proceedings of IMechE'03*, 2003 Washington D.C.
- Zurecki, Z., Ghosh, R. and Frey, J. H. 2004. Finish-turning of hardened powder metallurgy steel using cryogenic cooling. *International journal of powder metallurgy*, 40(1), 19-31.