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Cryogenic Manufacturing Processes

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Abstract

Cryogenically-assisted manufacturing processes are emerging as environmentally-benign, toxic-free, hazardless operations, producing functionally-superior products. This paper presents an overview of major cryogenic manufacturing processes summarizing the state-of-the-art and significant developments during the last few decades. It begins with a summary of historic perspectives, including definitions, scope, and proceeds to analysis of process mechanics and material performance covering tribological and thermo-mechanical interactions, followed by surface integrity, product quality and performance in cryogenic manufacturing. Process analysis and applications includes machining, forming and grinding. Economic, safety and health issues are then discussed. Finally, progress in developing predictive performance models and future outlook are presented.

Keywords: Cryogenic machining, Surface integrity, Modeling

1. Introduction

1.1. Historical perspective, definitions and application range

For over a century, the science and technology of producing low temperature environment is generally referred to as cryogenics, even though more scientific and precise definitions emerged later. The word "Kryos" has its Greek origin, meaning cold and frost. In 1877, Cailletet and Pictet (Paris) liquefied oxygen [1]. Heike Kamerlingh Onnes at the University of Leiden (Netherlands) was the first to build a cryogenic laboratory for the production of very low temperatures in 1882, and this lab became the leading center for cryogenics for over five decades. In 1898, Dewar (London) showed liquefaction of hydrogen, and in 1908, Heike Kamerlingh Onnes liquefied helium, which led to the discovery of superconductivity in 1911.

There are inconsistencies in identifying at what point on the temperature scale refrigeration ends and cryogenics begins. However, most research and standards organizations assume that it starts at or below −150 °C (123 K; −238 °F). Cryogenic Society of America defines cryogenic temperatures as being temperatures below 120^{0}K (-244^{0}F, -153^{0}C). Gunston [2], along with the National Institute of Standards and Technology (NIST) consider cryogenic temperatures below −180 °C (−292.00 °F or 93.15 K). This appears to be a logical dividing line, as the normal boiling points of numerous permanent gases (e.g., helium, hydrogen, neon, nitrogen, oxygen, and normal air) are all below −180 °C, while the Freon refrigerants, hydrogen sulfide, etc., have boiling points above −180 °C.

1.2. Origin of cryogenic material processing

Liquid nitrogen (LN_2) is most commonly used in cryogenics due to its widespread availability worldwide. The earliest use of liquefied gases as coolant in machining operations is reported by Reitz [3] in 1919 where carbon dioxide (CO_2) was used as a coolant in machining. During the WWII, scientists found that metals frozen to low temperatures showed more wear resistance. This led to the development of cryogenic hardening. In 1966, the term cryogenic processing was first introduced by CryoTech Company (Detroit, MI, USA), when they showed a 200%-400% increased life in metal tools by cryo-tempering. Cryogenic engineering application guidelines were established early in 1976 [4], and more recently by ASHRAE [5].

Despite these established definitions and practices, in processing operations, various researchers have used the term cryogenics to refer to temperatures below 0°C, largely including CO_2 applications [6-11].

The term, "cryogenic machining" was first used by Uehara and Kumagai in 1968 [12]. In machining operations, liquid gases such as nitrogen, carbon dioxide and helium are used as alternative coolants to traditional oil and water-based coolant/lubricants. Cryogenic machining aims at altering material properties of cutting tool and workpiece material and dissipate the heat generated at the cutting zone [13-15].

1.3. Sustainability concerns in manufacturing on the use of cutting fluids and progress in sustainable manufacturing operations

In recent years, using the principles of sustainability science and engineering in new product development has been an emerging trend in manufacturing. Designing sustainable products and developing sustainable manufacturing processes have been a major research focus in manufacturing. The indiscriminate and abundant use of cutting fluids in manufacturing processes and the associated costs and energy consumption has been a major sustainability concern.

1.3.1 Moving from flood cooling to dry and near-dry machining

The use of water as a coolant in machining processes dates back to 16th century [16]. However, the modern application of oil and water-based cutting fluids became common in the early 20th century in machining steel alloys. Cutting fluids lubricate the cutting zone to control abrasion and can improve heat dissipation from the cutting zone and therefore reducing the thermal and chemical wear mechanisms whilst improving part quality [17-21]. On the other hand, recent studies [22-24] have indicated that exposure to cutting fluids is related to the later development of various types of cancers, dermatitis and respiratory diseases. The most recent well-documented CIRP keynote paper by Brinksmeier et al. [25] reviews the progress made in developing metalworking fluids.

When coated cutting tools were introduced in the early 1970s, dry machining operations emerged as sustainable processes. However, with over four decades of active research and applications, dry machining has not yet found the widespread use, largely due to lack of effective coating materials and technologies and the ever-increasing application range. Near-dry machining (also known as MQL, Minimum Quantity Lubrication) emerged in the 1990s as a progressive and more sustainable solution to significantly reduce the amount of coolants/lubricants in machining applications. While the application range for such machining still continues to expand with improved machining performance in terms of tool-life, surface roughness, power consumption, etc., the actual effectiveness of such applications is somewhat limited. Also, the environmental and health effects of such mist application are still not well-known. Well-documented CIRP keynote papers on these topics can be found in Klocke and Eisenblatter [26], Byrne et al. [26], and Weinert et al. [28].

1.3.2 Significance and impact of cryogenic manufacturing

In cryogenic machining, which has been known to be the most sustainable process, a liquefied gas, typically LN_2, is used to replace conventional cutting fluids. Nitrogen is an inert, non-hazardous, non-toxic, non-flammable, colorless and odorless gas, which constitutes 79% of air [29-30]. It is lighter than air, and disperses into air after application, thus reducing the requirements for maintenance, post-machining cleaning and disposal [31-37]. Also, lower temperatures result in increased hardness and toughness in the cutting tool material, which in turn allows higher material removal rates, and therefore lower energy consumption and higher productivity [30, 38-40]. Recent studies report that cryogenic cooling has significantly improved the functional performance of machined components in terms of wear and corrosion resistance, and fatigue life [30, 40-44]. Fig. 1 shows the three major sustainable machining options.

Process performance depends very much on the coolant/lubricant application conditions influencing friction, temperatures, cutting forces, etc., and thus affecting tool-life, workpiece accuracy, and surface integrity of the components. Industrial use of such coolants/lubricants is largely limited to flood cooling with emulsion or oil.

The application of cryogenic media offers the advantage of dry machining in combination with rapid cooling effect. The two gases of CO_2 and LN_2 have to be distinguished regarding the mechanisms for generating low temperatures that imply different requirements for their use. A new aerosol strategy using small quantities of oil particles, in MQL form, combined with cryogenic CO_2 or LN_2, has also been developed during the last decade to provide lubrication of the cutting zone. Table 1 shows various cooling strategies and a comparison of sustainability concerns.

1.4. Scope and objectives of the paper

This paper is aimed at presenting a summary of recent progress in cryogenic manufacturing with a state-of-the-art review, focusing on fundamentals of cryogenic processing describing the process mechanics, product quality and performance of components produced from cryogenic manufacturing, major results from cryogenic manufacturing processes covering machining, grinding and forming processes and other hybrid processes. Also, summarized in the paper is the progress towards developing predictive performance models for various cryogenic manufacturing processes. Conclusions are drawn from the analysis of cryogenic manufacturing with a research outlook.

2. Process Mechanics and Material Performance: Tribological and Thermo-mechanical Interactions

2.1. Review and general background

Since the very early work by Uehara and Kumagai [12], for over two decades no significant progress was reported on cryogenic machining until the work by Chattopadhyay et al. [45]. Subsequently, Dillon et al. [13] presented a thermal and metallurgical analysis of the process on a few materials. Paul et al., [46-47] and Paul and Chattopadhyay [48-50] studied cryogenic machining and grinding processes extensively and reported on the benefits of tool-life, surface finish, dimensional accuracy and residual stresses on a range of steels. Significant work by Hong et al. [14-15, 20, 35, 37, 51-56] for almost a decade, during the 1998-2006 period, set the stage for revisiting the topic with future work. Their work spans over a range of topics covering the effects of *LN_2* cooling/lubrication on the machining process to achieve improved machining performance in terms of tool-life, power consumption, chip morphology and surface integrity. Also, early work by Wang et al. [57-58], Wang and Rajurkar [59-60] show the effectiveness of cryogenic cooling in machining a range of difficult-to-machine materials.

Fig. 1. Sustainable machining options.

Table 1. Effectiveness and applications of various cooling

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

The effect of cryogenic cooling on machining performance measures such as cutting forces, cutting temperatures, surface integrity, tool-wear, friction, etc., were studied extensively for various work materials such as *Inconel 718, Ti* alloys such as *Ti6Al4V,* various steels, refractory metals, *Ni-Ti* shape memory alloys, *Mg* alloys, bio materials such as *Co-Cr-Mo* alloys and composites [34, 40, 61-62]. In many of the reviewed publications it has been reported that cryogenic machining contributes to improved machining performance in various work materials in terms of cutting forces/power, tool-wear/tool-life, etc. However, from the product point of view, i.e., the potential contribution of cryogenic cooling on surface integrity characteristics of machined components, only lately researchers have begun studying this important aspect. For example, Bermingham et al. [63-64] show improvement in cutting forces, tool-life and chip morphology with use of cryogenic machining. Dhar et al. [65] and Dhar and Kamruzzaman [66] presented an analysis of cryogenic machining showing the positive influence on temperatures and machined surface characteristics. From the machining performance point of view, some conflicting results can also be seen (e.g., increased cutting forces, premature fracture of the cutting inserts, etc.). Extensive reviews on cryogenic machining and processing have been reported during the last decade [30, 34, 40, 61, 67] and therefore, only the most recent and highly- relevant progress will be reported in this paper.

This section presents a summary of material behavior in cryogenic manufacturing and the resulting metallurgical and microstructural transformation of work materials, including the tribological interactions and heat transfer mechanisms.

2.2. Material behavior, properties and performance, including formability and process characteristics

At low temperatures, properties of many metallic materials such as yield and tensile strength, hardness, wear and fatigue resistance are all enhanced in comparison with the properties at room temperature. In general, materials with a face-centered cubic (fcc) lattice keep their ductility at cryogenic temperatures, whereas body-centered cubic (bcc) and hexagonal-closed packed (hcp) materials become brittle. Furthermore, component properties such as dimensional stability increase, while residual stresses decrease. Several investigations of material behavior and changes in properties at cryogenic temperatures have been reported, with exemplary results presented [68-72].

Most improvements of properties are observed in steels [68-69, 73]. Bensley et al. [73] identified an enhancement of wear resistance of a case-carburized steel by cryo-processing of about 372%. A higher wear and fatigue resistance develop with a higher martensite content and formation of carbides [69]. The fatigue life of an austenitic stainless steel treated at -185°C could be raised up to 100 % [74]. Harish et al. [75] and Sri Siva et al. [76] showed an increase in the hardness of bearing steel about 14 % and 18%, respectively by cryo-processing, in comparison with the conventional heat treatment. The increase in hardness can be caused by an increased martensite content and greater precipitation of fine carbides, too. With a higher amount of martensite and precipitation of fine carbides, the tensile strength was shown to increase [69]. Bensley et al. [77] noticed a decrease in residual stress in case-carburized steel. With increasing amount of martensite, residual stress was reduced, because the instability of retained austenite at room temperature causes dimensional changes [78].

Fritsch et al. [79] noticed an enhanced degree of deformation for a high strength aluminum alloy by a factor of two at -196°C. In metals with a fcc lattice, adequate slip systems would exist at low temperatures [80]. Thermal and electrical conductivity is enhanced by processing at cryogenic temperatures, too [68-69]. The conductivity of a copper/chromium alloy increases by about 3-4% by cooling at -196°C [68].

To understand the differences in ductility at cryogenic temperatures, the crystal structure is examined. The ability of slip is dependent on the crystal structure. fcc metals slip at the {111}-planes and in the <101>-directions that are most densely packed. bcc metals slip at the <111>-directions that are closed-packed as well. At room temperature, the three slip-planes of bcc metals are mobilized. But, at cryogenic temperatures, the slip in bcc metals can be prevented by deformation twinning. The slip of hcp metals occurs at the (0001)-basal planes in the <11-20>-directions. Also, in hcp metals twinning appears likewise. In fcc and bcc metals, dislocation structures emerge. When a metal gets loaded, the dislocations dispose in a cell structure. With further loading, the dislocation density rises, the dislocations move to the cell walls, and the cell size shrinks. Moreover, the cell size decreases at lower temperatures. Compared to fcc metals, it is necessary in bcc metals to increase the strain for cell formation, when the temperature decreases. At cryogenic temperatures, the arrangement of dislocations is more uniform. The dislocations are located on definite crystallographic planes [80-82].

Forming processes at cryogenic temperatures lead to a greater dislocation density. During the forming process, dynamic recovery is suppressed. Thus, the ductility of the material increases. It is assumed that the density of defects remains at low temperatures and functions as recrystallization points. For ultrafine grains, less plastic deformation is necessary at cryogenic temperatures. Lee et al. [83] recognized that after cryo-rolling, an aluminum alloy includes a high dislocation density. The tensile strength increases from 315 to 522 MPa. The increased tensile strength can be explained by the suppressing of cross-slip or climb of dislocations, thus the dislocation density stays high. An annealing at about 150°C leads to recovery, a decrease in tensile strength from 522 to 471 MPa, and a rearrangement of dislocations. The grains are recrystallized and coarsened at 300°C and the tensile strength decreases to 340 MPa [79, 83].

2.3. Metallurgical and microstructural transformations, and dynamic recrystallization of materials in cryogenic cooling

A decrease in the amount of retained austenite, and an increase in the formation and precipitation of fine carbides lead to changes in material and component properties. Usually, up to about 10 - 20 % austenite remains in steels and cast iron by cooling. Cryo-processing induce the retained austenite to transform into martensite. Materials with a higher content of carbon have a lower martensite start and finish temperatures than room temperature. Austenite has a fcc structure, with greater ductility, and has a lower tensile strength than martensite that has a bcc structure. Austenite and martensite have a different size in the crystal structures, this results in a reduced stress when austenite transforms into martensite. A greater strength and hardness, but a lower ductility is reached. Retained austenite is unstable at room temperature, and it decomposes slowly. This decomposition can lead to dimensional changes as consequence of the differences in the crystallographic structure of austenite and martensite. Therefore, dimensional stability is optimized by cryogenic processing. In experiments with powder metal parts, the amount of retained austenite significantly declines from 49% to 3%. Meng et al. [84] show 12% retained austenite at the end of conventional heat treatment in a tool steel alloy, and 6% after cryogenic processing at -180°C.

During cryogenic processing, the amount of carbides formed from low temperatures increases. At low temperatures, the strain energy of martensite rises, and the carbon atoms move and form clusters. By heating back to room temperature, the clusters function as nuclei, therefore ultra-fine η-carbides form. These fine carbides are uniformly distributed. Carbides in general are characterized as hard and stable, but brittle and need a ductile matrix. After cryogenic processing, Meng et al. [84] observed fine carbide particles that are located mostly in the twin boundaries of the martensite matrix. Candane et al. [85] found fine precipitate carbides near grain boundaries of *AISI M35* grade *HSS* tool by cryogenic treatment at -195°C. With cryogenic processing, the microstructure changes to become a more uniform, refined and densed microstructure. Microfine carbides capture the remaining space in the voids and reduce in size, therefore vacancies arise in the crystal lattice. Paulin [86] observed such a behavior in frozen gears at -193°C.

Gill et al. [87] described the metallurgical and mechanical characteristics of cryogenically-treated *WC-Co* carbide by analyzing two different cryogenic treatments: a shallow cryogenic treatment at T = -110 °C for 18 hrs., and a deep cryogenic treatment at T = -196 °C for 36 hrs. Both cryogenic treatments affect a refinement of the hard phase particles of the tungsten carbide. It was shown that the hardness of the cutting material can be increased by about 4.75 % when applying the shallow cryogenic treatment, while the deep cryogenic treatment offers no significant increase in the hardness (only at about 0.21 %).

Thornton et al. [88] analyzed the influence of cryogenic treatment on the wear behavior of *H13A* (ISO K-type) tungsten carbide. The material was cooled in a nitrogen atmosphere at 1-2 K/min and held at 93 K/min for 24 hrs. Afterwards the material was gradually brought back to ambient temperature at a rate of 1-2 K/min. This treatment caused an increase in the hardness of about 9.2%. The increased abrasive wear resistance was explained in terms of changes in the cobalt binder phase.

Machai et al. [89] analyzed the influence of the heat treatment and the microstructure on the machinability of β-titanium *Ti-10V-2Fe-3Al.* A higher proportion of the secondary α-phase leads to an increased abrasive tool-wear. In addition to the flank wear, also crater wear can develop when machining solution-treated and aged β-titanium. This specific heat treatment leads to the development of a fine distributed secondary α-phase, which has an increased hardness. Machining with flood cooling leads to high thermal loads in the machined surface. Because of this, α-cases with a higher hardness can develop in the subsurface which can complicate the subsequent machining operations. However, under cryogenic conditions this mechanism is oppressed – see Fig. 2.

2.4. Tribological interface interactions and thermal aspects of cryogenic machining

The effect of cryogenic machining on tool-life has been investigated extensively for over a decade. In general, the application of cryogenic fluid, mainly LN_2, often leads to a significant decrease in tool-wear. However, it is not clear if this fluid can increase the tool resistance by a macroscopic cooling of all the components (cutting tool, chip, work material) [90], or if this cryogenic fluid modifies the local tribological conditions, especially the friction at the tool-work material interface as reported by Hong et al. [14]. Therefore, this section will summarize the state-of-the-art on the effects of cryogenic processing on friction at the tool-work material interface, and the heat transfer process.

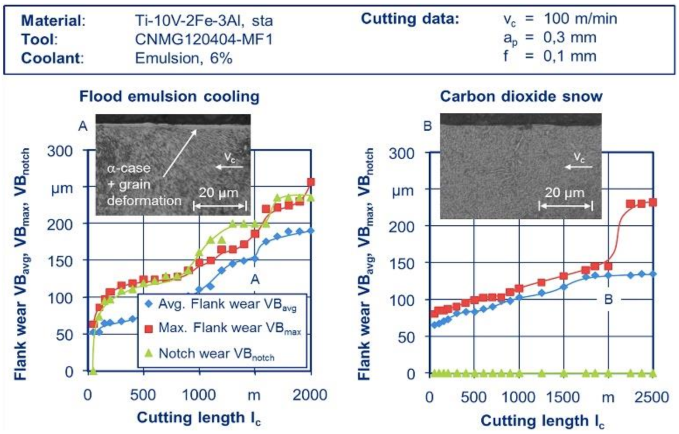

Fig. 2. Influence of cooling methods on the microstructure in the subsurface zone [89].

2.4.1. Friction at the tool-work material interface

Due to the developments in the emerging alternative lubrication techniques, the need for conducting extensive studies in the areas of friction was urged in early work by van Luttervelt et al. [91] and Childs et al. [92], and more recently by Brinksmeier et al. [25]. However, the characterization of friction coefficient in cutting remains an issue as discussed by Rech et al. [93]. Many researchers use the cutting process itself to evaluate an average macroscopic value of friction coefficient on the rake face based on forces measurements. This method has been used by Hong et al. [14] for cryogenic cooling/lubrication in machining of *Ti* alloys. Based on this approach, they report that when the cutting speed increases from 60 to 150 m/min, the friction coefficient decreases from 0.54 to 0.4 in dry conditions, whereas it varies from 0.24 to 0.21 under cryogenic lubrication. Also, they show that the friction coefficient depends strongly on the positions of the nozzle and the chip breaker, which leads to inconsistent values. The main limitation of this approach is due to the fact that cutting tests are only capable of providing macroscopic data with an average friction at the tool-chip interface. From cutting and feed forces, it is very difficult to discriminate the role of the work material flow-stress modified by the very low temperatures (e.g., hardening effect as suggested by Shokrani et al. [34]), and of the various contact zones, including the assumed dead metal zone around the rounded cutting edge and the rubbing zone on the flank face. Hong et al. [14] suggest a combination of cold strengthening of titanium and of a decrease of the friction coefficient at the interface without establishing the relative importance of both mechanisms. Therefore, it is difficult to use friction coefficients identified by this method in modelling applications such as finite element analysis (FEA) cutting simulations. A few other authors prefer using an inverse method to determine friction coefficients by comparing cutting and tangential forces obtained experimentally and numerically. In the case of machining of *Ti6Al4V* alloys with carbide, Rotella et al. [95] did not observe any influence of the cryogenic lubrication on the friction coefficient. They identified a friction coefficient of 0.6 in both cases.

In machining of *AZ31B Mg* alloy, a friction coefficient of 0.7 was identified by Pu et al. [96] with or without cryogenic lubrication. A small decrease in the friction coefficient from 0.6 to 0.58 is reported by Rotella et al. [97] for cryogenic machining of *AA7075* alloy. Validation of these methods is however extremely complex, and therefore the applicability of these findings largely remain uncertain.

Other authors, who prefer using a tribometer, independent of any cutting process, were able to simulate conditions (pressure, velocity, open tribo-contact) as those occurring along the tool-work material interface. Based on a pin-on-disc set-up, the tribological interaction between a *Ti6Al4V* alloy with a carbide tool has been investigated by El-Tayeb et al. [98]. They observed that friction increases from 0.4 to 0.6 by increasing contact pressure (normal force varies from 6 to 23 N) and/or sliding velocity (8 to 60 m/min). They also observed an increase in friction coefficient compared to those obtained in dry air conditions. To the contrary, Hong [20] observed a significant decrease in the friction coefficient for the same material pair on a pin-on-ring system. Unfortunately, such tribometers are not fully relevant to characterize friction coefficients in cutting due to their 'closed tribosystem' configuration [93]. Also, the contact pressures are limited, and can hardly reach the ones observed in cutting. On the contrary, based on a dedicated 'open tribometer', and by applying a high normal load (1000 N), Courbon et al. [99] observed that friction decreases as the sliding speed increases, as shown in Fig. 3. They also observed that *Ti6Al4V* alloy leads to intense adhesion, and that LN_2 or gas nitrogen could decrease neither friction coefficient nor adhesion, irrespective of the sliding velocity compared to a dry air condition. As a consequence, they conclude that nitrogen cannot decrease the mechanical load on cutting tools or enable the frictional heat transfer to carbide tools.

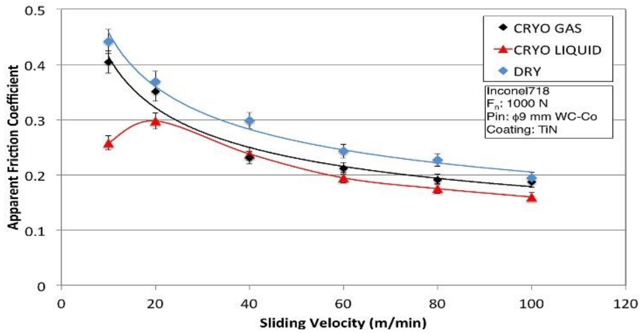

Fig. 3. Influence of cryogenic lubrication on friction of *Ti6Al4V* alloy and *TiN* coated carbide pin [99].

Regarding the Inconel 718 alloy, Courbon et al. [99] observed that nitrogen decreases the friction coefficient and adhesion. They also established that liquid phase nitrogen provides a lower friction coefficient than gas phase nitrogen. Cristino et al. [100] suggest that nitrogen protects the freshly machined surface from chemical reaction between the two materials or with the environment (oxygen), and thus avoids the welding phenomena due to very low temperatures. This protective effect seems even more effective when the surface roughness of the cutting tool is very low (R_a < 0.1 µm). Other authors such as Shokrani et al. [34] assume that the LN_2 evaporates quickly at the cutting zone, which may create a hydraulic cushion between the two contact surfaces.

2.4.2. Thermal aspects of cryogenic machining

It has been known that cryogenic fluid at best only partially penetrates the tool-chip interface through a network of interfacial capillaries, and/or by diffusion through the primary deformation zone. This reduces the cutting temperature T_c by: (a) reducing the cutting energy u_c, and (b) enhancing the capacity of extracting heat from the cutting zone. Cryogenic machining of ductile materials at temperatures below its recrystallization temperature activates the first mechanism by Rebinder effect; thus reduces the fracture strain of the work material [101], and consequently u_c. The second mechanism of heat extraction is proportional to the coefficient of heat transfer CHT *'h'* and the difference between the coolant fluid temperature t_f and the surface temperature t_s of the hot body. Conventional flood coolants have temperatures t_f around +25°C, giving LN_2 (t_f=-196°C) a -220°C advantage, rendering the tool an effective heat sink. The mechanism of heat transfer in CM produces relatively high CHT through absorbing latent heat, and then warming the gas from the boiling point to room temperature [102]. The evaporation of the cryogenic coolant forms a gas cushion (GN_2) at the tool-chip interface that functions as a lubricant [103].

Delivery of the Cryogenic Cutting Fluid

To control the cutting temperature T_c, conventional cutting fluids are usually applied along the directions as follows: (a) over the flowing chip, (b) over the primary deformation zone on the chip, (c) at the tool-chip interface, or (d) at the tool flank – work interface. Cryogenic fluid, in the liquid or gas state, can additionally be impinged directly onto the tool insert outside the chip/tool interface, or its back through the tool holder (Hong and Ding, 2001a). This provides the flexibility of cooling the workpiece material or the tool separately. While the fluid delivery in the directions (a) through (c) represent the condition of "confined flow", direction towards (d), and impingement on the tool insert represents a "free flow" (or open flow) condition. This distinction has a strong influence on the dynamics of fluid flow and the mechanism of heat transfer.

Cryogenic Fluid Flow and Heat Transfer Mechanisms:
Fluid Flow Characteristics

Free flow condition: The open flow field of an impinging jet is characterized by three regions (Fig. 4(a)) [104]. The *free jet region*, where the 'potential dense core' is observed (*L/D* = 4-6), *the stagnation region* and the *wall jet region,* where the flow is in the outward radial direction. In this region, the development of boundary layer from the stagnation point has a strong effect on the heat transfer rate. Shear driven entrainment of surrounding fluid establishes a coherent structure of vorticities around the jet. In cryogenic machining (CM), the jet is thermodynamically in the liquid phase at the exit, and injected into *subcritical pressure*, but *supercritical ambient temperature*. When the ratio p/p_{cr} is as small as 0.03, the jet width is relatively small and has a classical liquid-like appearance and very fine ligaments and possibly drops are ejected from the jet – see Fig. 4(b) [105-106]. The gas dissolved in the liquid increases the heat transfer in sub-cooled boiling [102].

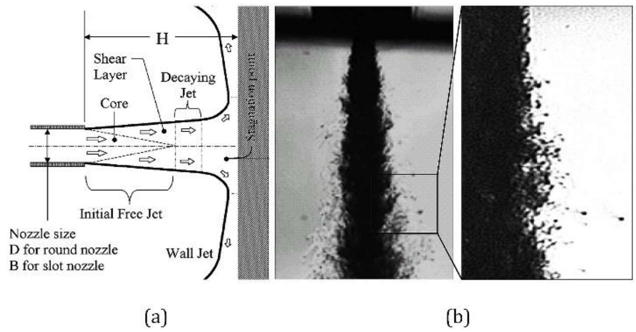

Fig. 4. (a) Flow regions of an impinging jet [104], (b) LN_2 at sub-critical pressure GN_2 [106].

Depending on the jet temperature, the length of the dense core of the jet is about 10 times the injector diameter. Therefore, in practical applications, the surface of the hot tool insert is likely inside the potential core region, where the jet cooling capacity is maximum. For such highly subcritical condition ($p_{env} << p_{cr}$), the jet behaviour follows the classical liquid breakup theory [105]. When the hot target is located at a distance of approx. 40 times the jet diameter, it is estimated that the nitrogen is about 50% liquid by the time it reaches the target. This change causes 1 to 2 orders of magnitude increase of the fluid's volume. This expansion has a beneficial chip-clearing effect, especially in applications that limit the use of forced air, such as deep pocketing of aerospace structures [107].

Film boiling under an impinging LN_2 cryogenic jet was investigated by Barron and Stanley [108] showing that the relationship between the average CHT for a jet impinging on a circular plate is governed by the following relation: $Nu_{avg} = 0.0885\ Re^{0.45}\ Pr^{1/3}$, where *Re* and *Pr* are Reynolds and Prandtl numbers, respectively, which depend on the nozzle exit diameter d, the mass flow rate *m*, and the thermal and physical properties of LN_2 and the target material.

The heat transfer process in cryogenic jet systems was also investigated by Dreitser [109] for a wide range of LN_2 nozzle diameters, flow velocities and target surfaces temperatures. Through flow visualization, it was shown that a liquid film layer is formed over an area of 1-5 times the jet diameter, depending on the jet average velocity and surface inclination angle. The CHT was found to be 1,700-6,500 W/m^{2}K; i.e., 10 to 40 times higher than at boiling in the natural convection.

Investigation of transient response behaviour of jet impingement was carried out in recent publications by Haustein et al. [110] and Lu [111]. It was shown that the time duration of the cryogenic fluid in contact with the workpiece is very short and the surface cooling rate is very high; 4 to 8.5°C/ms (Lu, 2014). Lu [111] also concluded that at the tool-chip separation point, the surface CHT is very small and rapidly increases with the distance (Fig. 5).

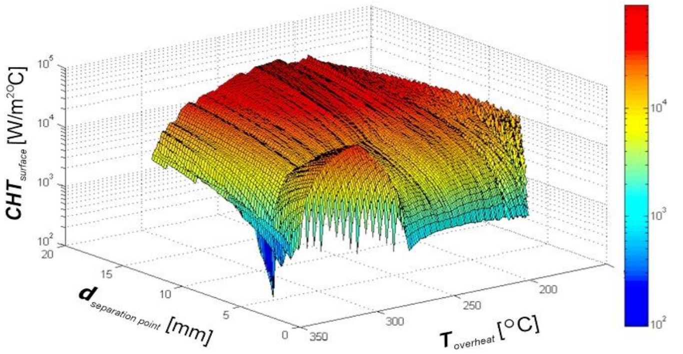

Figure 5. Surface heat transfer coefficient at 51.7kPa driving pressure.

The surface CHT in the open region could reach 5x10^4 W/m^{2}K, which is more than an order of magnitude higher than typical convection cooling. Recently, CFD analysis of the multiphase flow of LN_2 was carried out [112] for nozzle diameter, *d* = 2mm, flow rate = 1 l/min, and at a distance of 15 mm from a hot surface at 700 K. The flow characteristics are shown in Fig. 6; namely, the velocity streamlines and vector plot, turbulence, and liquid void fraction. The cooling rate at the target hot surface at the intersection with the centreline of the jet is estimated to be around 2°C/ms. The CHT at the same point is 4.9x10^4 W/m^{2}K, and decreases along the wall jet at a rate of 600 W/m^{2}K/mm.

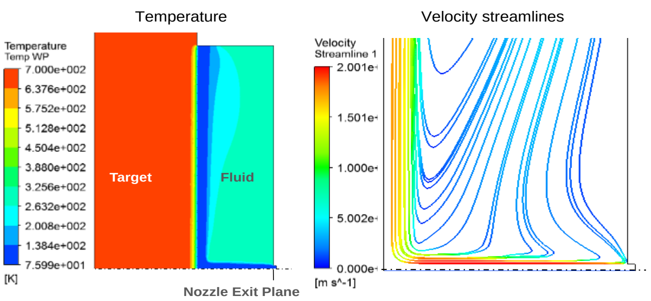

Fig. 6. Cryogenic flow characteristics [112].

The fully developed region of the boiling curve in forced convection coincides with the extrapolation of the pool boiling curve [113]. Nucleate boiling data of *LN2* for pool and forced convection boiling are given in [114].

<u>*Confined Flow:*</u> The characteristics of a LN_2 jet from a tube confined in a larger tube, impinged onto heat transfer surfaces of different conditions were investigated by Zhang et al. [115]. In this confined configuration, 180° change in the flow direction in a very short time causes a strong exchange of the fluid momentum, leading to the intensive perturbation to the heat transfer surface. With a gradual increase in the surface temperature, the flow regime enters transitional boiling region when the critical heat flux (CHF) is reached. It was shown that the heat transfer capability and CHF increase with the increase in the LN_2 jet velocity due to the increase in the jet turbulence intensity. In confined jet impingement, the nucleated bubbles coalesce together and form slug and bubble column, while the nucleate boiling heat transfer is suppressed, and the heat transfer process is dominated by convective evaporation versus nucleate boiling.

In restricted or confined flow, the presence of the wedged opening (or crevice) introduces another dimension to the problem complexity, since heat conduction in the narrow gap can be the dominant mechanism, as demonstrated by Attia and D'Silva [116]. A solution approach to this nonlinear problem, which involves sub-cooled nucleate boiling, was to predict whether nucleate boiling is taking place in the crevice region.

Heat transfer coefficient

As the main objective of the cryogenic fluid is to dissipate the heat generated during the cutting operation, the quantification of the heat transfer between the cryogenic fluid with the cutting tool and the machined surface remains an issue to be addressed. Among the common heat transfer mechanisms (radiation, conduction, convection) between a material and the cutting fluid, the wide majority of researchers focus their attention on convection (natural or forced convection) characterized by its heat transfer coefficient expressed in W/m^{2}K [90]. It is well known that the liquid cryogenic fluid can evacuate more heat than gas [99] due to its high specific heat and dynamic viscosity [117]. However, even if a pure liquid phase is applied in the cutting zone, evaporation still occurs in contact with hot surfaces, inducing a vapor cushion [118]. This gas film has a poor capacity to evacuate heat [64]. Thus, it becomes clear that the liquid pressure and velocity at the exit of the nozzle (high Nusselt and Reynolds numbers) and its orientation become key parameters to eliminate this boundary film [119]. This is confirmed by several studies such as the one by Hong et al. [14],] and Shokrani et al. [34], who report the large influence of the nozzle position and orientation on tool-wear. Also, the same phenomena may occur inside the delivery channel. The cryogenic fluid at the delivery exit may be either gas, liquid or a mix of gas and liquid, which makes it difficult to model the heat transfer process in the cutting zone. Therefore, Pusavec et al. [120] developed a phase sensor to monitor and characterize the cryogenic fluid phase.

The determination of heat transfer coefficients by a direct approach is quite difficult. Therefore, some researchers prefer using an inverse method to determine the heat exchange coefficient by comparing cutting temperatures obtained experimentally and numerically. In the case of *Ti6Al4V* machining, Rotella and Umbrello [95] reported a value of 20000 W/m^2.K for cryogenic cooling (NB: the ratio between the liquid or the gas phase has not been characterized), and a value of 20 W/m^2.K for free air convection, whereas Sun et al. [121] report a value of 2000 W/m^2.K for dry compressed air. In machining of *AZ31B Mg* alloy, a heat transfer coefficient around 50000 W/m^2.K was found more appropriate [96]. Rotella and Umbrello [97] reported a heat transfer coefficient of about 200 W/m^2.K when machining *AA7075-T651* alloy.

The wealth of information in the literature on force convection boiling should be examined in the context of enhancing the heat transfer process in cryogenic machining. It was shown, for example, that roughing or coating the surface to be cooled with a thin layer (40-100 μm) of low thermal conductivity material can increase the CHT [109]. Alternatives to the conventional cryogenic LN_2 cooling that have been used in other applications need to be re-examined for CM. This includes the use of cryogenic gas nitrogen, and the combined LN_2 and air supply where the liquid droplets possess relatively high inertia gained from the air streamlines. With increasing mass flux of the liquid, boiling/evaporative wetting evolves and a thin liquid film is formed around the stagnation point [112]. Significant heat transfer enhancement could be materialized through a single or multiple pulsating turbulent impinging jets, where very complex flow fields, with alternating generation of vortex rings and suction back into the nozzle, can be realized with fluidically generated pulsating jets [123-124]. Fig. 7 is a compilation of some of the relevant data published in the literature for the range of CHT values. For the sake of comparison, typical CHT values for free and forced convection in a single flow regime, MQL, and air quenching are also presented, along with those for metal-to-metal thermal contact conductance In addition to its economic and environmental advantages, Fig. 7 also demonstrates the effectiveness of cryogenic machining.

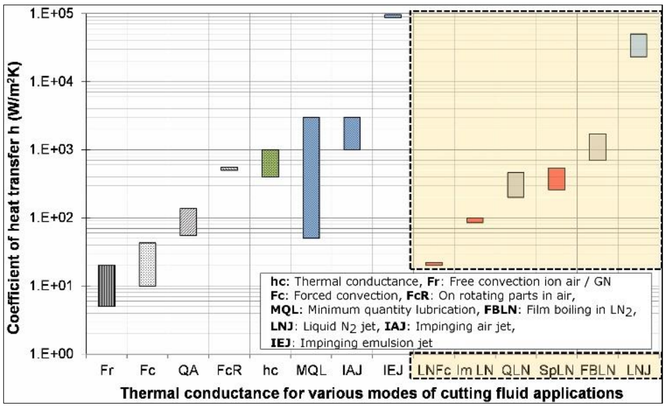

Fig. 7. Typical values of CHT in various cooling regimes.

3. Surface Integrity, Product Quality and Performance: *Surface and Sub-surface Modifications and their Impact on the Functional Performance of Components*

3.1. Surface integrity enhancement

Among all benefits achieved from cryogenic processing of materials, the most significant benefits come in various forms of surface integrity enhancement. Numerous recent studies on cryogenic processing of a range of materials have consistently shown improved surface integrity in terms of microstructural and phase transformations, surface and sub-surface hardening, generation of a severe plastic deformation layer and compressive residual stresses within these layers, etc. [39-40, 125-130].

Klocke et al. [129-130] studied and analyzed the cryogenic machining performance titanium aluminide in terms of surface roughness/integrity, chip morphology, cutting forces and tool-wear. It has been shown that a significant surface roughness reduction was achieved in cryogenic cooling, also in comparison with MQL – see Fig. 8.

From the observation of the surface roughness profiles and the machined surfaces from the beginning to the end of the tests, the deterioration of surface quality due to tool-wear was clearly evident in dry conditions. With a heavily worn tool, surface cracks with a characteristic dimension of about tens of microns appeared. It was shown that these unsatisfactory results could be averted by the adoption of a cryogenic cooling/lubrication strategy resulting in a stable cutting process, which reduced the flank wear decisively. The cutting force analysis shows a rapid increase in dry machining as a result of tool-wear.

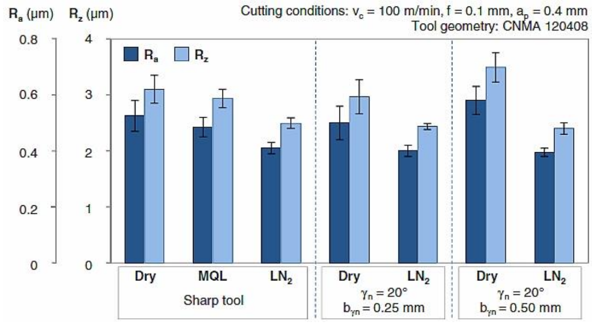

Fig. 8. Surface roughness in machining of *Ti-45Al-8Nb-0.2C-0.2B* alloy [129].

Truesdale and Shin [131] conducted milling experiments with LN_2-based cryogenic coolant to study the effect on the machining process for *Udimet 720.* These cryogenic milling experiments yielded positive results by increasing the maximum cutting velocity from 10 m/min to 120 m/min. Microstructural analysis confirmed that the smearing and plucking mechanisms are retarded by the slowing or elimination of the diffusion process.

Grzesik et al. [132-133] analyzed the machining and burnishing performance of pre-cooled hardened *AISI 5140* steel and found that it leads to increased surface roughness, contrary to the previous findings, presumably due the effect of increased hardness and strengths as well as coarser microstructure of the frozen workpiece. Also, it has been observed that in dry hard turning, the maximum micro-hardness is localized close to the surface whereas for cryogenic cooling, the trend is to shift this point beneath the surface and with the cryogenic pre-cooling of the workpiece the white layer is not produced. Ghosh et al. [134] also explored the effects of cryogenic coolants in machining hardened materials (*AISI 52100* steel and *A2* tool steel), from an industrial perspective, with alumina ceramic and *PCBN* cutting tools. Substantial benefits of LN_2 cooling, both in terms of tool-life and surface roughness, were observed. The enhanced performance of cryogenic machining is attributed to more efficient heat removal from the cutting tool insert, as well as reduction in thermal softening of the cutting tools. Umbrello [127] and Rotella et al. [39] have also studied the cryogenic machining performance of *AISI 52100* steel, focusing on machined surface alterations. Their results show that the surface integrity characteristics can be improved and that white layer is either partially reduced or totally eliminated under certain process parameters with cryogenic cooling conditions. The effectiveness of cryogenic machining in limiting white layer thickness is attributed to rapidly lowering the cutting temperatures thus avoiding martensitic phase changes.

Dhananchezian and Kumar [135] studied machining of high-temperature titanium alloy, *Ti6Al4V* in a turning process with specially prepared cutting tool inserts, and by using of cryogenic cooling method. They found that the cutting temperature and surface roughness were reduced by 61–66% and 36%, respectively, over machining with flood cooling. The cutting force was also decreased by 35–42% while the flank wear was reduced by 27–39% in cryogenic cooling over flood-cooled machining. The direct application of LN_2 into the heat generation zones, through holes made in the cutting tool insert, was considered to be more effective over conventional machining.

Bermingham et al. [63] show that the main cutting force was reduced with cryogenic cooling. However, the thrust force was significantly increased with no change in the feed force.

Additionally, the friction coefficient was shown to be increasing in cryogenic conditions. The explanation for such a behavior was that the lower cutting zone temperature in cryogenic led to less localized thermal softening occurs compared to dry cutting.

Aramcharoen and Chuan [136] studied the machining performance of *Inconel 718,* in milling process. Cutting force, cutting temperature, tool-wear, machined surface quality, chip formation and energy consumption were compared with dry and conventional oil-based coolant assistant machining. Also, they observed higher forces in cryogenic machining. The reason for higher forces was explained in terms of higher material strength at lower temperature, when using cryogenic cooling in the primary shear zone. On the other hand, with conventional coolants, the heat in the shear zone cannot be quickly removed, and thus elevated temperature results in plastic deformation in the work material with material softening. Similar observation trends have also been reported by Pusavec et al. [137] and Kaynak et al. [40].

Kaynak et al. [40, 138-142] conducted extensive study on cryogenic machining of *NiTi* shape memory alloys. They showed that cryogenic machining significantly improves the surface integrity in machined components in terms of increased microhardness, phase transformation temperatures, surface quality and strength of the material, power consumption, etc. In their study on tool-wear, Kaynak et al. [139] studied and analyzed the main cutting force variation over cutting time. The smallest variation has been observed in the MQL condition. However, cryogenic cooling generates significantly lower absolute cutting force, and it is still very consistent over the cutting time in comparison with dry and MQL machining. Also, it was shown that cryogenic cooling reduced the tool-wear rate at high cutting speeds, particularly the progressive flank wear at the nose region and notch wear at the depth of cut line. Fig. 9 shows the comparison of notch wear progression in dry, MQL and cryogenic machining of *NiTi* shape memory alloys.

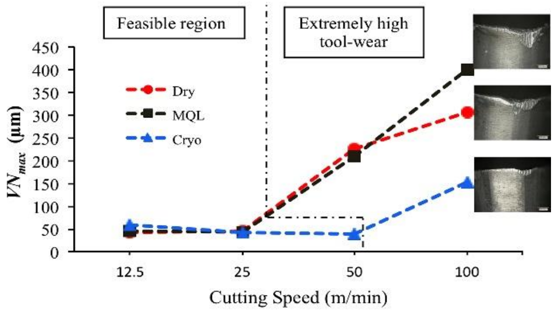

Fig. 9. Comparison of notch wear progression in dry, MQL and cryogenic machining of *NiTi* shape memory alloy [139]

Fig. 10 shows the comparison of crater wear on the tool face of the cutting tool and the flank wear progression at the nose region after 3 minutes of machining in dry, MQL and cryogenic machining of *NiTi* shape memory alloy, again showing the lowest tool-wear rate in cryogenic machining (Kaynak et al., 2013).

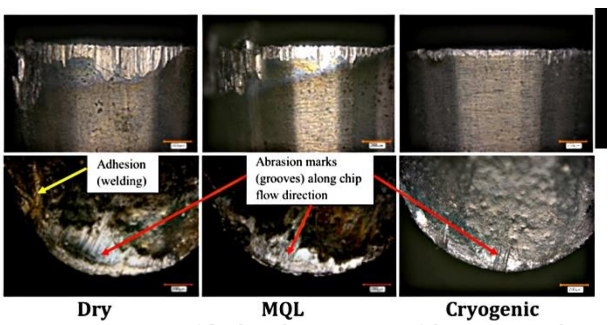

Fig. 10. Comparison of flank and crater wear of the cutting tool in dry, MQL and cryogenic machining of *NiTi* shape memory alloy after 3 min. of machining [139]

3.2. Product quality requirements

The compliance of defined quality requirements is the most important objective of the metal working industry. Thus, the machining process is only as good as the quality of the machined surface and sub-surface. This section will present some important requirements for surface qualities in major applications. The general requirements concerning the surface integrity in material removal processes have recently been compiled in a recent CIRP keynote paper [143]. In this paper some exemplary requirements for aircraft industry will be shown.

To increase the lifetime of the components, a reliable manufacturing process is necessary. One example is the insertion of inherent compressive stresses into the subsurface. These stresses can increase the dynamic lifetime of an aero-engine components about 2-3 times (Fig. 11). Another example is plastic deformation in the subsurface zone. Unsuitable machining operations can lead to strong plastic deformations, which reduce the service life of engine components [144]

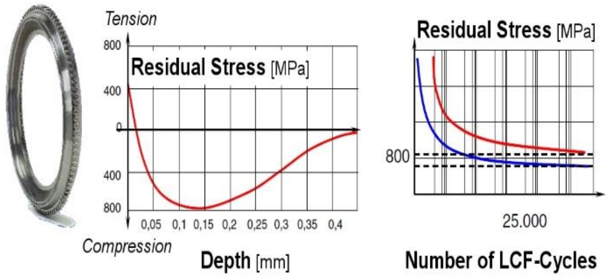

Fig. 11. Increase of service time by residual stresses [144].

Several investigations show the effect of machining process on the fatigue life of the machined components. Hardy et al. [145] studied and analysed the influence of the integrity of machined surfaces on the fatigue performance of the Powder Nickel alloy *RR1000 and* showed that white layers in the microstructure significantly reduce the fatigue performance.

Safety-relevant components such as turbine discs require extensive measurements and quality monitoring to satisfy the specified high product quality. In industrial applications the material quality is tested by ultrasonic measurements. After the forming process and the heat treatment a first machining operation is carried out to achieve the ultrasonic contour. This contour enables the detection of small internal material faults such as micro-cracks, blowholes or deviations of the grain size. A surface roughness of $R_z < 3.5$ μm after the machining process is required for this application [146].

3.2.1. The impact of cryogenic processing on product performance

The effects of cryogenic temperatures on phase composition and hardness of metallic materials has been investigated intensively since the 1970s [68, 147]. Numerous investigations have been carried out to determine the effects of cryogenic processing on tool-life. However, the number of investigations concerning surface integrity is somewhat limited. Mainly, machining processes such as turning, drilling and grinding have been investigated [40]. Furthermore, burnishing processes [148-149] and deep rolling [150] have been carried out at cryogenic temperatures. Among the investigated materials, low alloy steels [47, 151-153], *Ti-6Al-4V* [14, 57], stainless steel [37, 154] nickel-based alloys [155-156], magnesium alloys [41-42], bio materials such as *Co-Cr-Mo* alloys [44, 128, 148], CFRP [157], powdered metal [158-161], *AISI 52100* hardened steel [43, 127], *AA7075* alloy [97], and other materials can be found. An extensive review on the effects of cryogenic machining on surface integrity has been published recently [40]. Therefore, the following section will be limited to general aspects and selected experimental results.

3.2.2. Micro/nano structure, grain size and grain orientation

Pu et al. [41] showed the potential of using cryogenic machining to control the microstructure on the surface and subsurface layers of *AZ31 Mg* alloy. Cooling method and the edge radius of the cutting tool were found to have a significant influence on the microstructure resulting from machining as shown in Fig. 12. In particular, Fig. 12(d) shows that in the affected layers grain structures were not discernible with both optical and *SEM* pictures. Under the same cutting conditions, dry machining did not produce any such affected layer (Fig. 12(b)).

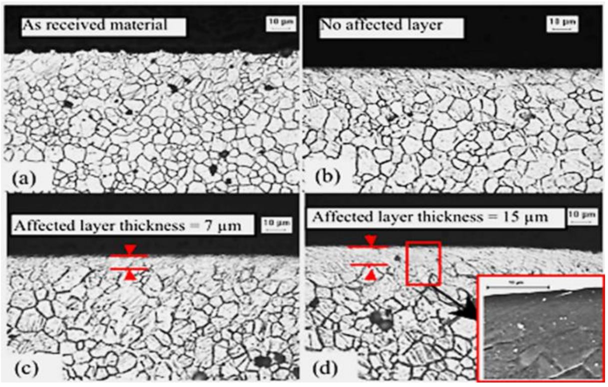

Fig. 12. Microstructure of *AZ31 Mg* alloy: (a) As received material before machining, (b) Dry machining, cutting edge radius = 30 µm, (c) Cryogenic machining, edge radius = 30 µm, and (d) Cryogenic machining, edge radius = 70 µm [41].

No differences in the chemical composition of this layer, compared with the bulk material were found from the analysis of energy dispersive spectroscopy. It was found that the nanocrystalline grains were about 31 nm in size in this layer. In cryogenic machining, the hardness in the affected layer increased to about 95 HV from 55 HV in the bulk material.

Cryogenic temperatures lead to significant changes of mechanic material behavior, such as enhanced tendency to twinning in materials with low stacking fault energy [162] and – depending on the material – increased 0.2% yield stresses, and more pronounced work hardening [163]. Thus, temperature has major impact upon the microstructure obtained from cryogenic machining. Grain refinement can generally be achieved by processes, which lead to severe plastic deformation (SPD). If surface-near grains are refined with diameters in the nano range, the layers are often denoted as "nanocrystalline surface layers". Ambrosy et al. [164] observed remarkable grain refinement in cryogenic machining of low alloy steel *AISI 4140*. The influenced surface layer was 3.2 µm thick compared to 2.2 µm at dry machining. Pu et al. [41] reported on the formation of ultrafine-grained surface layers on an *Mg-Al-Zn* alloy.

3.2.3. Hardness

Increased hardness was obtained from cryogenic machining of a range of work materials. Hardness could be increased due to work-hardening as well as grain refinement. Increased hardness values were also achieved by Pusavec et al. [137] during their investigation on the *Ni*-based super alloy *Inconel 718*. In their experiments, they compared dry and minimum lubrication (MQL) turning with cryogenic turning, and found that after the latter, the work-hardened surface is harder, but thinner than after dry and MQL machining. This was confirmed by Klocke et al. [165] who found a reduction in the affected surface depth in *γ-TiAl*. Similar results were also found by Fredj and Sidhom [166] in cryogenic grinding of *AISI304* stainless steel. Significant increases in hardness from cryogenic machining of *Mg* alloys [41-42] and in cryogenic burnishing of *Co-Cr-Mo* biomedical alloy [148] have been reported. Rotella et al. [167] conducted a comparative study of machining of *Ti6Al4V* alloy under dry, MQL and cryogenic cooling conditions for a range of cutting conditions to establish the effect of cooling conditions. Their results show a much deeper affected harder layer under the same conditions – see Fig. 13.

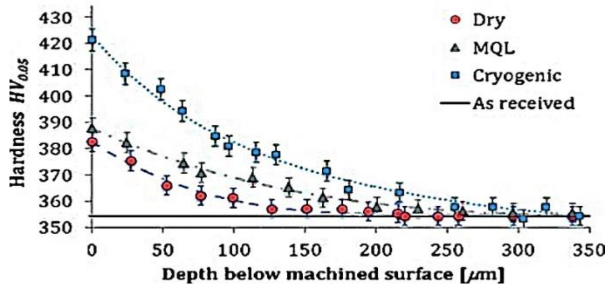

Fig. 13. Comparison of surface and subsurface hardness profiles in machining of *Ti6Al4V* alloy under dry, MQL and cryogenic cooling conditions at 150 m/min. cutting speed

Yang et al. [44, 128, 148] reported that Severe Plastic Deformation (SPD) processes have been used to modify the surface integrity properties of materials by generating ultrafine or even nanometer-sized grains in the surface and subsurface region. Cryogenic burnishing was shown as an effective SPD process. Experimental studies and analysis on *Co-Cr-Mo* biomedical alloy show that LN_2 application during the burnishing process significantly improved surface roughness, increased hardness, produced a thicker burnishing-influenced surface layer, with significant grain refinement.

3.2.4. Residual stresses

The major effect of cryogenic machining is that it can lead to grain refinement with stable and thick nanocrystalline surface layers, combined with compressive residual stresses. Besides, the described increase of hardness and compressive residual stresses can be achieved by SPD processing, including machining and burnishing. It has long been known that mechanical plastic stretching leads to compressive residual stresses, whereas heat leads to tensile residual stresses [168]. Fredj and Sidhom [169] conducted cryogenic grinding experiments and found tensile residual stresses parallel to the machining direction were reduced by 50%, compared to conventional machining.

Umbrello et al. [170] found shallower residual stress profiles in cryogenic machining of hardened *AISI 52100* steel, compared to dry machining, whereas Bicek et al. [153] have observed higher compressive stresses in the external layer from a cryogenic hard turning operation, compared to a dry operation. Pusavec et al. [137] studied machining of *Inconel 718* under different machining conditions in terms of residual stresses parallel and perpendicular to the machining direction after dry, MQL and cryogenic turning. It was shown that cryogenic cooling increases the compressive residual stresses significantly (Fig. 14).

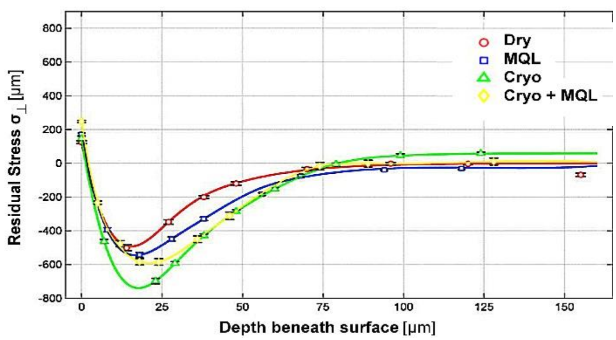

Fig. 14. Residual stress distributions after machining of *Inconel 718* [137].

Outeiro et al. [171] studied the process mechanics and surface integrity induced by cryogenic machining of *AZ31B-O Mg* alloy, and established the effects of cutting speed, undeformed chip thickness, cutting edge radius, etc. Their measured in-depth residual stress profiles in circumferential and axial directions obtained under a range of cutting conditions and cutting edge radii. Almost for all conditions generated compressive residual stresses up to 20 microns below the machined surface.

Pu et al. [41-42] focused on surface integrity induced by cryogenic machining, while surface integrity factors have been proved to remarkably influence the functional performance of magnesium alloys, including corrosion/wear resistance and fatigue life. Compared with the initial material, cryogenic machining contributes to: (i) improved surface finish; (ii) significant grain refinement from 12 um to 31 nm in the featureless surface layer with the formation of nanocrystalline grain structure; (iii) large intensity of (0002) basal plane on the machined surface; (iv) significantly larger compressive residual stresses at greater depths – see Fig. 15, and (v) increased hardness in the surface layer. It was also shown that cryogenic burnishing of this *Mg* alloy provides the above benefits with corrosion resistance.

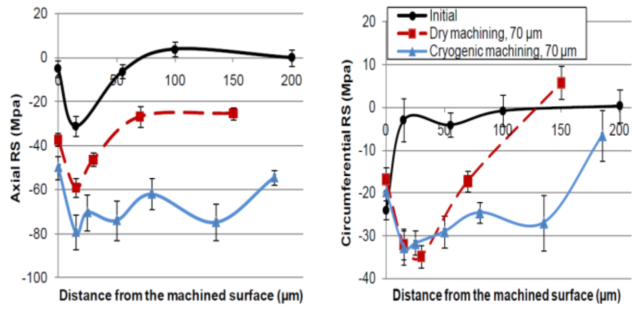

Fig. 15. Comparison of residual stresses before and after cryogenic machining of *AZ31 Mg* alloy using a tool with 70 μm edge radius (b) circumferential and (c) axial direction [41]

3.2.5. Phase transformation

It has long been known that cryogenic cooling of a hardened workpiece can transform retained austenite to martensite, leading to increases in hardness [68]. However, it was shown that the increase in hardness after deep cryogenic processing can only partly be due to the transformation of retained austenite. Increased hardness can possibly be explained by the formation of carbides. Meng et al. [84] found the formation of eta-carbides at twin boundaries of martensite at cryogenic temperatures. Thus, carbide formation from the initially formed martensite has been used to explain the increased hardness [68].

Some attention has been given to the formation of white layers during hard machining processes. These zones result from rapid heating and quenching, leading to untempered martensitic structures [170]. Based on their findings on *AISI52100* q+t to 60 HRC, Zurecki et al. [172] concluded that cryogenic machining could lead to a significant reduction of white layer thickness. Umbrello et al. [170] investigated orthogonal dry cryogenic machining of *AISI 52100* steel, and found decreased white layer thickness combined with an increased ratio between compressive residual stress depth and white layer thickness.

Kaynak et al. [138] studied the effect of cryogenic machining on the phase transformation behaviour of *NiTi* shape memory alloys using differential scanning calorimetry (DSC). They measured the transformation temperature of the machined surface and subsurface, and show that in cryogenic machining *NiTi* alloy is in martensite phase, while in dry machining it is in austenite phase, thus a large difference exists between the two processes.

A comparative study of machining of *Ti6Al4V* alloy conducted by Rotella et al. [167] under dry, MQL and cryogenic cooling conditions for a range of cutting conditions includes an analysis of XRD patterns for some of the conditions tested where the □ and □ phases are identified according to Bragg's law and the published data. Fig. 16 shows a sample of XRD results obtained demonstrating these effects.

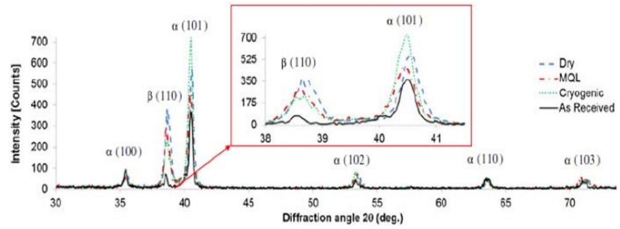

Fig. 16. XRD results obtained for machined samples at V_c = 150 m/min, f = 0.05 mm/rev [167].

3.2.6. Surface quality and integrity – Machining of porous materials and powder metals

Schoop et al. [158-161] studied the effect of cryogenic machining on the surface integrity of porous tungsten, a sintered powder metal. By controlling the cryogenic pre-cooling time, workpiece temperature and tool rake angle, they were able to fine-tune the surface morphology of 80% dense porous tungsten [160]. Nevertheless, Schoop et al. [161] noted that achieving a specific cutting temperature during cryogenic machining was more efficiently implemented by controlling the cutting since the pre-cooling may result in undesirable thermal contraction of both the workpiece and the machine tool system. While dry machining was limited to v_c < 50 m/min due to excessive tool-wear, Schoop et al. [158] were able to achieve cryogenic high speed machining of porous tungsten at cutting speeds up to v_c = 400 m/min with drag finished PCD cutting tools (r_β = 10 μm), as shown in Fig. 17. When cryogenic cooling was used, no thermal damage occurred on either the machined (sub-) surface or the temperature sensitive PCD cutting tools. Beyond a critical cutting speed of approximately 250 m/min, the researchers proposed that a brittle to ductile material transition of the tungsten workpiece material resulted in significantly lower tool-wear and surface roughness. By using cutting speed to alter the cutting temperature, Schoop et al. [158] were able to carefully control the mode of machineng – see Fig. 17

3.3. Functional performance of manufactured components

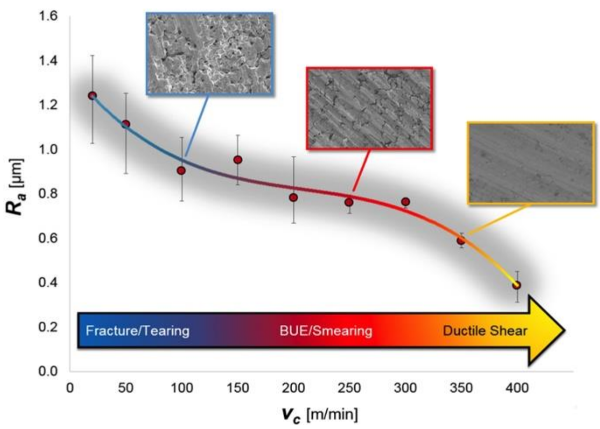

Fig. 17. Control of the mode of machining through cryogenic high speed machining of 80% dense tungsten powder metal [158].

3.3.1. Wear resistance

Cryogenic processing have been used as alternative treatment to enhance wear resistance on cutting tools, tooling, moulds and dies, as well as on final parts. Seah et al. [173] performed a series of experiments to investigate the effect of cold and cryogenic treatments on the performance of uncoated tungsten carbide tool inserts in turning of 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. Leskovsek et al. [174] studied the effect of tempering temperature and cryogenic treatment on the *M2 HSS* tool, and reported that generally cryogenic treatment improves the HSS tool-wear resistance. Da Silva et al. [175] reported that cryogenic treatment increased the HSS drill tool-life from 65% to 343% until catastrophic fracture. Sreerama Reddy et al. [176] investigated the effect of cryo-processing on the performance of multi-layer coated *WC* tool inserts in turning operations. They reported that cryo-processing significantly reduced the flank wear of the inserts as compared to non-treated inserts. Ramji et al. [177] and Firouzdor et al. [178] cryogenically treated HSS tool and 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 during drilling of grey cast iron and carbon steel, respectively.

Yong and Ding [179] investigated the effect of cryogenic treatment on *WC–Co* cemented carbides. The experimental results show that cryogenically-treated tool generates higher wear resistance. Lal et al [180] conducted a comparative study on wear resistance of cryogenically-treated tool and die steels with standard heat treated samples. They found that untempered samples show a higher life on those firstly tempered and then cryogenically-treated. Also, cryogenic treatment done at 93^0 K generated a 20% longer life with respect to the maximum life achieved through cold treatment. Barron [181] applied cryogenic treatments on nineteen metals (12 tool steels, 3 stainless steels and 4 other steels). The tool steels exhibited a significant increase in wear resistance after the soak at 77^0 K, and a less dramatic increase after the 189^0 K soak. There was an increase in the wear resistance after the cryogenic treatment for the stainless steels, but the difference between the two treatments was less than 10%. The plain carbon steel and the cast iron showed no improvement after cryogenic treatment. Vimal et al. [182] made an investigation on the effect of cryogenic treatment on *En 31* steels done at different stages of heat treatment. It was observed that through cryogenic treatment the wear can be decreased by a maximum of 75% depending on the service conditions. Their study also confirmed that the cryogenic treatment should be done before tempering immediately after quench hardening to obtain maximum benefits.

Yang [183] investigated the effect cryogenic burnishing process on the wear performance of a *Co-Cr-Mo* alloy due to the burnishing-induced surface integrity properties. When the samples (initial, dry burnished and cryogenically burnished) were compared for wear performance on a pin-on-disc equipment, cryogenic burnishing led to the highest wear resistance – see Fig. 18.

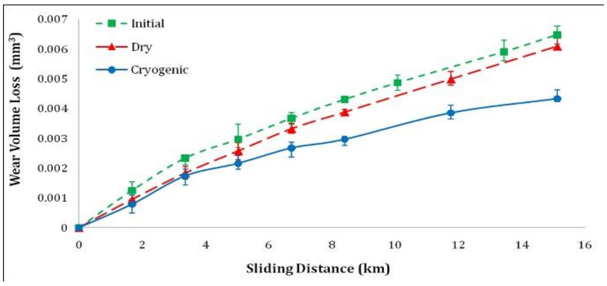

Fig. 18. Comparison of wear performance of cryogenic burnishing with dry burnishing of *Co-Cr-Mo* alloy [183]

3.3.2. Corrosion resistance

Influence of cryogenic treatments on corrosion resistance have been investigated during the last decade since the corrosion resistance is one of the requirements for the materials used by the chemical, medical, and structural/construction industries. Fredj et al. [166] evaluated the ground surface quality improvements of the austenitic stainless steel *AISI 304* resulting from cryogenic cooling. They found that a reduction of more than 40% of R_a was achieved, a higher level of work hardening occurred, and a lower tensile residual stress was measured with better resistances to stress corrosion cracking and pitting corrosion.

Zieliński et al [184] investigated the effect of laser surface remelting at cryogenic conditions on the microstructure and corrosion characteristics of the non-ferrous alloys. They found that laser remelting at cryogenic conditions generally resulted in increased corrosion resistance in aluminum, copper and titanium alloys due to the generation of ultra fine-grained microstructure in the remelted layers, consisting of supersaturated solid solutions and small quantity intermetallic phases, which limit the formation of corrosion cells.

Pu et al. [41-42, 96] focused their studies on magnesium alloys and found that specimens burnished with cryogenic cooling show much better corrosion performance in comparison with as-received material and dry burnished materials. They reported that improved corrosion resistance was due to enhanced microstructural and surface/subsurface quality involving basal structure increasing the resistance of cryogenically machined components against corrosion. Comparison of corrosion tests on samples from grinding, dry burnishing and cryogenic burnishing shows the high corrosion resistance in cryogenically-burnished samples (Fig. 19).

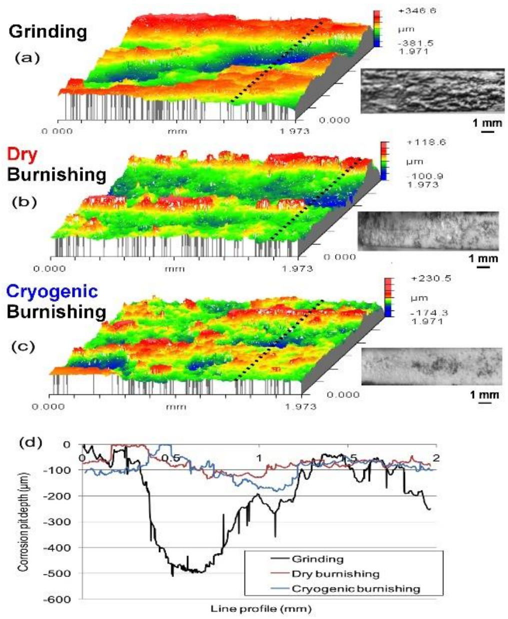

Fig. 19. Surface morphology of *AZ31B Mg* processed by different treatments after immersion in 5 wt % *NaCl* solution for 200 hrs: (a) ground; (b) dry; and (c) cryogenically-burnished samples; (d) corrosion pit depth profiles along the dotted lines [42].

Singh et al. [185] investigated the effects of deep cryogenic treatment in conjunction with the heat treatment on the corrosion rate, hardness and tensile strength of the mild steel. Their results show that after deep cryogenic treatment, the corrosion rate and mechanical properties of the samples were all improved. Zhang et al. [186] studied the effects of cryogenic treatment on corrosion resistance. The static soak results show that the corrosion rates of the LC4 *Al* alloy in 3.5% *NaCl* solution before and after cryogenic treatment are 0.152 mm/a and 0.135 mm/a respectively, indicating that cryogenic treatment boosted the corrosion resistance.

3.3.3. Fatigue life

Cryogenic processes generally induce large and deep compressive residual stresses on the surface layer, which should further enhance the functional performance of the components such as wear and corrosion resistance and fatigue life. Zhirafar et al. [187] investigated the effects of cryogenic treatment on the mechanical properties and microstructures of *AISI 4340* steel. Mechanical tests, including rotating fatigue, impact and hardness were carried out, after various heat treating conditions and the results were compared. It was shown that in general, hardness and fatigue strength of the cryogenically treated specimens were a little higher (of the order of 25–30MPa at lifetimes of approximately 10^7 cycles), whereas the toughness of the cryogenically-treated specimens was lower when compared to that of the conventionally-treated steel. Baldissera and Delprete [188] studied the deep cryogenic treatment effects on fatigue and corrosion resistance of the *AISI 302* austenitic stainless steel (in hardened and solubilized conditions) and found that deep cryogenic treatment produced significant positive effects on the fatigue behaviour of the solubilized material while slight differences were noted for the solubilized group.

Rotella et al. [97] reported the effect of cryogenic machining on fatigue performance of machined *AA 7075-T651* components. They calculated the fatigue life for various cutting parameters for dry and cryogenic machining, considering the effect of grain size. Their calculation showed that cryogenic machining helps to improve the fatigue life of these components. Later, Rotella [189] extended her work to a multiphase alloy*s,* such as the *Ti-6Al4V* alloy, and found that cryogenically-machined samples resulted in larger number of cycles to initiation, while the dry machining often results in the smaller. Yong and Ding [179] studied the evolution of the mechanical, magnetic and fatigue properties behaviours of *WC–Co* alloy samples during cryogenic treatment. Their findings show that the alloy exhibits higher fatigue life after cryogenic treatment than those untreated.

3.3.4. Other functional performance measures

In general, in the published literature, cryogenic machining is reported as a favourable process to improve the mechanical properties of engineering and tool materials, the surface quality, reduce the surface roughness, and to obtain better surface topography for various materials.

Zhang et al. [186] investigated the effects of cryogenic treatment on mechanical properties of *LC4 Al* alloy and found that this treatment increased the compressive yield strength of the material. Wang and Rajurkar [60] reported that for several materials such as *Ti-6Al4V*, *Inconel 718* and *Tantalum*, application of cryogenic cooling during their machining substantially reduced the surface roughness in comparison with dry condition. Cryogenic machining of conventional steels has also shown to produce better surface quality due to its positive effect on reducing tool-wear and built-up-edge [15, 190].

Pusavec et al. [137] reported that cryogenic machining of *Inconel 718* alloy helps to reduce the surface roughness by preventing mechanical and chemical degradations of the machined surface in comparison with dry and MQL conditions. Rotella et al. [95] found that the surface roughness obtained in cryogenic machining of *Ti-6Al4V* alloy was consistently superior to those obtained in dry and MQL machining, and at higher cutting speeds, MQL produced comparable results. The overall surface roughness for all three cooling conditions is always below 0.3 μm, which was shown to prevent the initiation of cracks under cyclic loads. Similar results were also found when the machinability of *AA 7075-T651* were investigated under dry, MQL and cryogenic conditions [97].

Klocke et al. [165] reported that due to reduced tool-wear in cryogenic cooling conditions, better surface quality and much more consistent topography was obtained. Also, Kaynak et al. [138] showed that cryogenic machining provides reduced surface roughness in machining of *NiTi* shape memory alloy.

4. Cryogenic Applications in Various Manufacturing Processes: *Surface and Sub-surface Modification and Performance Enhancement*

4.1. Machining processes

4.1.1 Materials and methods used in turning, milling and drilling

In general, cryogenic cooling in machining operations is conducted by both using an external jet or delivery of the coolant through the machine tools' spindle and cutting tool. Majority of academic research in cryogenic milling operations is concentrated on using external jets as these can be easily retrofitted into existing machine tools [38]. However, industrial application of cryogenic cooling in milling operations is based on the delivery of the cryogen through the spindle of the machine tool [191] as this would allow for precise delivery of the cooling medium onto the cutting edges and the cutting zone. In this case, insert type cutting tools are used on a specially designed tool holder, which sprays a cryogen onto the cutting surfaces of the cutting tools.

A review of the literature [34] shows that a majority of studies on cryogenic milling used coated tungsten carbides in machining experiments. Shokrani et al. [23] used *TiAlN* coated solid carbide end mill for cryogenic milling of *Inconel 718.* Huang et al. [192] used solid carbide end mills for machining *AA7075* aluminium alloy, and reported that cryogenic cooling increases the stability of the tool during machining. They reported that lower chatter marks were detected on the workpiece using cryogenic cooling as compared to dry machining.

Aramchareon and Chuan [136] used a two-flute *TiN* coated solid carbide end mill with an external cryogenic jet for machining of *Inconel 718.* They reported that in comparison with dry and conventional flood cooling, cryogenic machining with LN_2 resulted in improved tool-life and surface integrity. Tests have also been carried out with *CBN,* diamond and ceramic tools, but it is hard to find studies that demonstrate improved efficiency with more advanced and expensive tool materials. The major reason for the use of carbide tools is price vs. performance. Also, in the early work by Zhao and Hong [193-194], where mechanical properties and microstructures of several commercial tungsten carbide and high speed tool steel grades were evaluated over a range of temperatures, down to cryogenic cooling conditions (-196°C).

It has been observed that carbide tool materials generally maintain their transverse rupture strength and impact strength, while the hardness increasing significantly as the temperature decreases. Most carbide grades tested, showed increased crack resistance at cryogenic temperature. The quantity of the binder material was shown to have a predominant effect on the cryogenic transverse rupture strength of certain carbide grades.

However, there were also some successful applications of cryogenic machining on ceramic tools. Ghosh [134] studied the effects of cryogenic cooling on tool-life in machining of hardened steels at high cutting speeds. In machining of hardened *A2* tool steel (62 HRc) with alumina ceramic tools, it was observed that tools under cryogenic cooling significantly outperformed dry and flood-cooled cutting operations. This was attributed to the increase in bulk hardness of the cutting tool and reduction in thermal softening. However, it was observed by the researchers, somewhat surprisingly, that a cryogenically-cooled ceramic tool outperformed all other tool/cooling methods with increasing feeds in experiments designed to test the tool fracture toughness. Contrary to prior machining research and teachings on fluid coolants, a cryogenic jet impinged on the rake surface did not induce fractures, chipping or cleavage of oxide-based ceramic tool materials. This increase in fracture toughness was explained as due to a combination of the following factors: (i) cryogenic hardening of the entire tool material, (ii) reduction in thermal expansion-driven stresses within the entire tool, and (iii) reduction in thermal gradients at the tool surfaces due to the boundary film effect and the Liedenfrost phenomenon.

When using *Al_2O_3*-based cutting tools, it has been observed that these tools gave an extended tool-life and better surface roughness than the *CBN* tools, in machining with LN_2 [172]. Abelle and Schramm [6] employed liquid CO_2 with *PCD* for cutting the ferrous material compacted graphite iron *(CGI).* Normally this combination of tool and workpiece materials is avoided because of the high graphitization of the diamond matrix. With the use of liquid CO_2, the critical temperature is not reached, if a defined field of cutting speed and grain size/binder content is observed.

Even though the carbide tools are most popular, different cutting tool producers are starting to conduct research on developing specific cutting inserts (geometry and grades), specifically for cryogenic machining. Some of them already support industry with special cryogenic machining cutting tools, including end mills, face mills, high-feed mills, thread mills, drills and turning tools.

4.1.2 Experimental work and major findings from cryogenic machining of composites and other non-metals

The freezing of the workpiece can be realized in a closed cryogenic bath, cryo-chamber, general cryogenic flooding, or supplying a cryogenic medium on the chip. Further, this effect can be improved by supplying the cryogenic coolant to the cutting edge and rake face, in order to improve chip breaking performance (Bhattacharyya et al., 1993). Besides better chip breaking, machining performance with carbide tools is improved due to reduced tool-wear, as well as good surface quality. While machining low carbon steels, the feed range could be expanded in a way that the preferred chip-forms/shapes could be produced. Additionally, it has to be noted, that the workpiece cooling can lead to an increase of cutting forces and undesirable microstructural changes. An increase in cutting force during turning of Kevlar composites was reported, as well as an increase in torque while milling of *AISI 304* stainless steel [195-196]. More recent work by Xia et al. [157] shows reduced tool-wear and improved hole quality in cryogenic drilling of carbon fiber-reinforced plastic (CFRP) composite material.

4.1.3. Operational characteristics of LN_2 and CO_2 cooling processes

The two gases, LN_2 and CO_2 commonly used for rapid cooling in machining differ considerably with respect to the mechanisms of refrigeration. Therefore, different requirements have to be considered concerning coolant application through the machine tool spindle and the cutting tool into the cutting zone.

Carbon dioxide (CO_2) is stored as a liquid in medium pressure tanks (approx. 57 bar) at ambient temperature. For process cooling it is supplied via pressure-resistant pipes into the cutting tool. Machine elements and the supply lines are not thermally influenced at all as long as the medium is under pressure. When CO_2 expands at the exit of the cooling channels of the tool, the pressure drops and a phase transformation occurs from liquid carbon dioxide to a mixture of gaseous and solid CO_2. A cooling effect and temperatures as low as -78.5°C can be reached due to this phase transformation and the Joule-Thomson effect. Since the solid CO_2 is sublimating at ambient temperature, cryogenic cooling with CO_2 is residue-free.

When applying LN_2, totally-different cooling characteristics have to be considered. Nitrogen has to be stored in insulated tanks because at ambient pressure it converts from the solid into the liquid phase at -210°C and starts boiling at -196°C. For this reasons LN_2 is more suitable for cooling at very low temperatures. However, this behavior causes specific problems for the application as an effective coolant. First, all supply lines and machine elements, as well as the cooling channels of the tool, have to be insulated to avoid hazards and decreased cooling capacity, and secondly, when coming into contact with surfaces, which have a much higher temperature, the Nitrogen vaporizes. This leads to an insulating gaseous film on the surface, which reduces the cooling effect.

In comparison with CO_2, using LN_2 results in a much longer starting time until the system is cooled down, as shown in Fig. 20. The application of CO_2 allows the beginning of the cutting process after approximately 60s. After this time, a minimum temperature of approx. -50°C can be reached. Since the large volume of vaporized Nitrogen has to exit, the cooling channels of the cutting tool, the time until the system is ready to start is much longer when using LN_2. Even after reaching an exit temperature of approx. -170°C, the cooling process is not stable due to the gaseous Nitrogen which is generated in the supply system.

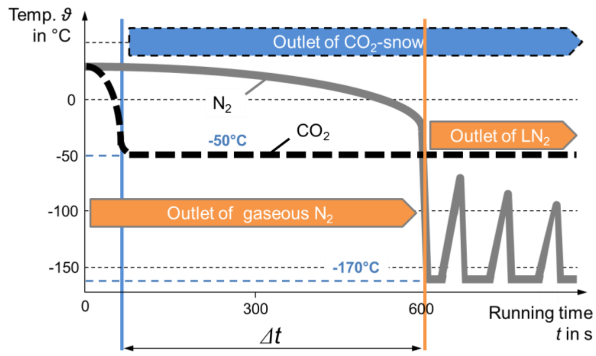

Fig. 20. Temperature profile of LN_2 and LCO_2 at coolant exit.

Table 2 summarizes the relevant properties of these two cooling methods to distinguish the fundamental differences between CO_2 and LN_2 as cooling media.

Table 2. Properties of CO_2 and LN_2 relevant for cutting

	Carbon dioxide (CO_2)	Nitrogen (LN_2)
Min. temperature	-78.5°C	-196°C
Cooling effect	Formation of low temperatures during expansion at tool exit	Cooling of the storage tank, feeding tubes and cutting tool
Handling /integration into machine tool	No insulation required	Insulation of all components is necessary
Tools	Standard tools with only few modifications	Special tool design with insulation

4.1.4. Performance comparison of LN_2, CO_2 and high-pressure (HP) cooling processes with conventional flood cooling

The consumption amount of nitrogen or other coolants as spray can be very small, especially in comparison with flood cooling. However, to reach the thermal equilibrium state of heat generation and dissipation, a correct combination of conditions such as coolant flow rate, energy levels, nozzle position(s) and location(s) are also necessary [6]. Jerold and Kumar [190] report that the application of cryogenic cooling by CO_2 and LN_2 resulted in a reduction of cutting temperature in comparison with conventional flood-cooled (wet) machining. Cryogenic LN_2 coolant reduced the cutting temperature by about 9–34%, and 3–17%, when compared to flood-cooled and CO_2 machining conditions, respectively. Cryogenic CO_2 cooling reduced the cutting forces more effectively than cryogenic LN_2 machining by about 2–12%.

Several researchers liken the performance of a CO_2-snow cooling when machining materials with low heat conductivity. Patil et. al. [197] analyzed the effectiveness of compressed CO_2 in machining tests with *Inconel 718.* They compared the CO_2-cooling with dry machining and showed the influences on the microhardness developed in the subsurface zone: dry machining leads to a lower hardness, while the CO_2-cooling produced an increase of about 25 % in comparison to the hardness of the bulk material. Machai et. al. [89] used CO_2-cooling when machining β-titanium *Ti 10V 2Fe 3Al,* and compared with results from flood cooling.

Klocke at el. [130] presented the potential of modern lubri-coolant strategies for use in wider applications, comparing conventional flood cooling with high pressure assisted machining and CO_2 machining performance. The quantification of the potential is for external longitudinal turning process of austenitic stainless steel *X5CrNi18-10*. Focus of the work was an analysis of tool-wear and measured forces, as well as chip breakability. It has been observed that in machining, the cooling/lubrication fluid pressure has a major and positive role on tool-wear, cutting forces and chip formation. As a consequence, high pressure-assisted machining leads to significant increase in tool-life. Simultaneously with lower wear rate, high-pressure jet-assisted machining increases the stability of the process providing more effective chip breakage, starting at pressures 4-8 MPa. In terms of energy efficiency and costs, it is important to optimize the flow rate and pressure. In a specific case, the optimum pressure and flow rate were 15 MPa and 31 l/min, respectively. In CO_2-assisted cryogenic machining of stainless steel, significant tool-wear reduction has been achieved. Fig. 21 shows a comparison of tool-wear progression between CO_2–based cooling and conventional flood cooling with emulsion.

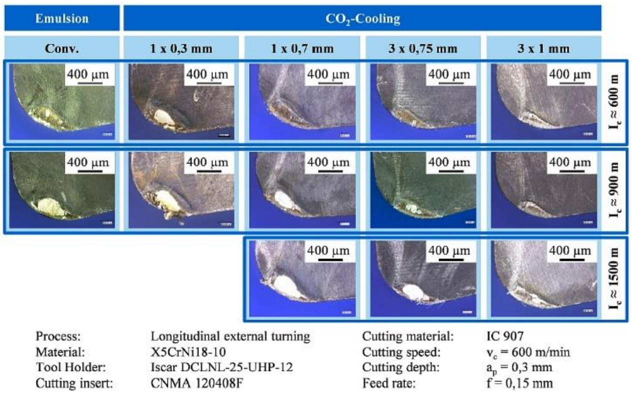

Fig. 21. Tool-wear progress in machining austenitic stainless steel using emulsion flood cooling and *CO_2* cooling [130].

Similarly, in machining of *Inconel 718*, the temperatures in proximity of 0.5 mm from the cutting edge have been measured for different cooling-lubrication conditions [137]. Cryogenic machining was shown to outperform dry, flood and MQL. Kramer [198] compared different cooling lubrication strategies on a *Ti6AlV* titanium alloy in turning operations. His results show that tool-life performance in all three alternative cases (HP, CO_2 and LN_2) was better than conventional machining. Even though the CO_2 can prolong the tool-life, the best performance were obtained with high pressure jet assisted machining and LN_2 cryogenic machining. A similar trend was seen also in cutting forces and temperatures.

A comprehensive analysis of CO_2 internal supply, and the influence of nozzle requirements on the cooling effect have been performed by Putz et al. [199-200]. The cooling performance was investigated as a function of the tool cooling channel diameter, distance from jet exit and time with regard to physical and thermodynamic influencing factors.

In the experimental set-up, the CO_2 internal supply was realized as a snow jet guided through the cooling channel in a carbide tool and directed onto a copper plate. In order to determine the temperature distribution of the cutting zone, tools with cooling channels of 0.75 mm and 1 mm bore diameter, as well as an axial distance range between the jet exit to the copper plate of 5 mm to 20 mm, were tested. Results show that a diameter of the cooling channel of 0.75 mm and a shorter distance between the CO_2 exit and the cutting zone can lead to lower temperatures compared to a diameter of 1 mm with a higher CO_2 flow rate. Considering the tool design, the effect of CO_2 cooling can be increased by realizing a distance of the CO_2 exit to the cutting zone designed as small as possible, and by using a cooling channel diameter smaller than 0.75 mm. At a small distance, higher focusing enables significant cooling in the central part of the flow, but considerable cooling is also detected at the measuring points further away in the radial direction from the central flow as shown in Fig. 22. The correlation between flow intensity of the CO_2 snow jet, and temperature of the cutting zone was verified by a mathematical model [200].

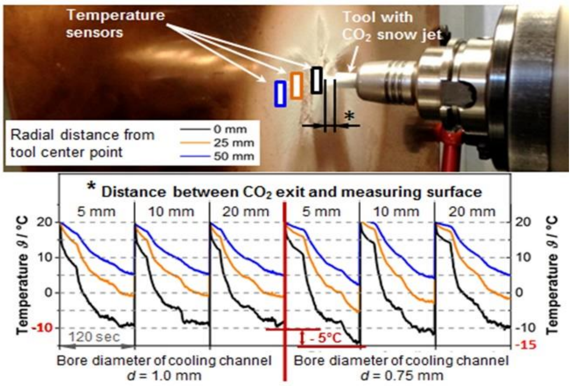

Fig. 22. Influence of cooling channel diameter, radial distance from jet center and distance between CO_2 jet exit and impact surface on the measured temperature [199].

Based on the results from experiments and simulation, it can also be concluded that the orientation of the tool cooling channel orthogonal to the cutting edge is most effective for cooling of the cutting zone. An orientation of the cooling channel with a smaller or larger angle leads to an overflowing of the cutting zone with the cooling medium, resulting in a considerably reduced heat transfer. In turn, this means that more cooling medium is required to achieve a comparable cooling effect.

A step further is a system that is capable of delivering MQL and CO_2 through the spindle, as well as control the temperature/cooling effect. This system is presented in the patent from Cool Clean [201]. However, in both cases, the adaptation of the rotary unit to the machine tool (milling or drilling) spindle is required. In addition to the solutions for supplying CO_2 and MQL through the spindle of milling and drilling machine tools, some tool making companies are launching on the market new tools that have appropriate CO_2 channel sizes and directions (Fig. 23).

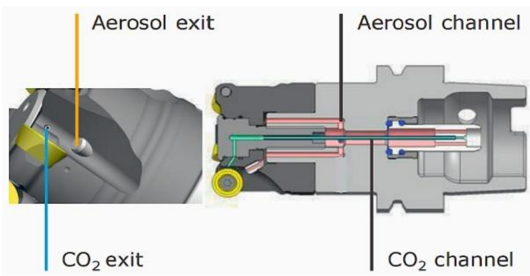

Fig. 23. Water Cryo-tecTM cutting tool holder.

A recent attempt in this regard has been Cordes, et al. (2014), where machining performance of CO_2 milling of the high temperature high strength stainless steel 1.4962 (*X12CrNiWTiB16-13*), used by turbine industries, have been analysed in terms of the tool-wear of cemented carbide tools, the cutting tool and chip temperatures, and the chip formation mechanism. The results show lower tool-wear, possibility to increase the productivity and lower temperatures..The workpiece surface from the dry machining process shows significant adhesions, while this effect was not observed in the cryogenically-machined surface (Fig. 24).

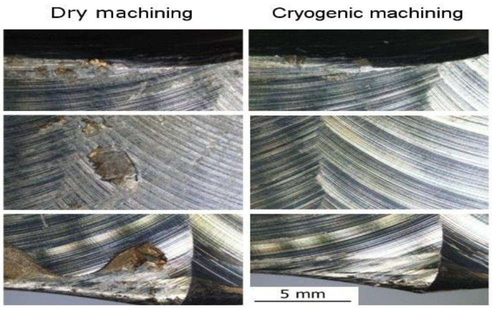

Fig. 24. Comparison of quality in *CO_2* and dry milling of *X12CrNiWTiB16-13* workpiece (Cordes, et al., 2014)

4.1.5. Performance comparison with MQL applications

Dry or near-dry (MQL) machining options are frequently proposed as a sustainable alternative to conventional flood machining, However, for difficult-to-cut materials, the cooling effect is questionable. Pusavec et al. [137] conducted experiments on machining *Inconel 718* to show the comparison of tool-life for different cooling conditions: dry, MQL, flood, and cryogenic conditions. In all cases, CLF was delivered on the cutting tool rake face. It was shown that the behavior of dry and MQL cooling is relatively comparable, which means that even when using MQL instead of dry machining, the process does not sufficiently remove the heat generated in the cutting zone. In flood-cooled machining it is possible to almost double the tool-life in comparison to dry machining (70% increase), while the cryogenic machining offer an additional increase (60%) in tool-life.

In machining of Titanium alloys *Ti-5553,* Sun et al. [202] compared the machining performance and analyzed different cooling/lubrication strategies (flood, MQL and cryogenics with LN_2). Up to 30% reduction in cutting forces has been observed in cryogenic machining, and compared to flood and MQL. MQL, it provides better surface roughness as higher ductility could be achieved due to the elevated temperatures.

Kaynak et al. [139] analyzed the machining performance (tool-wear, forces, and surface quality) in cryogenic machining of *NiTi* shape memory alloys (SMA), and compared with dry and MQL machining. Analysis of the machining performance with carbide tools show lower tool-wear in cryogenic machining -- see Fig. 25.

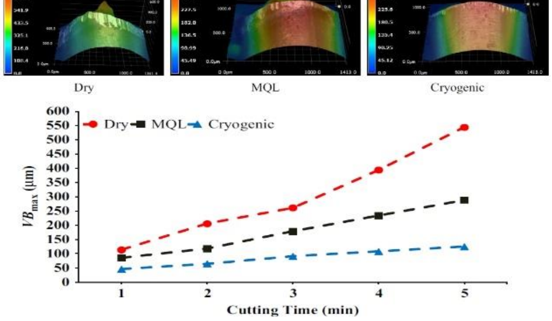

Fig. 25. Tool-wear in machining of *TiNi* shape memory alloy (Carbide KC5410, f = 0.05 mm/rev, a_p = 0.5 mm, V_c = 25 m/min) [139].

Additionally, the cutting force comparison showed comparable for dry and MQL machining, while it was about 35% lower than MQL for cryogenic machining. In analysing the surface quality degradation with the progression of the tool-wear, it has been observed that the maximum increase in surface roughness occurred under dry condition. Additional observation from LN_2 cryogenic machining performance in conventional, HP and MQL machining of *γ-TiAlN* machining show that MQL, in terms of of tool-wear, was comparable with conventional machining, while cryogenic machining with LN_2 using carbide tools can decrease the tool-wear rate by about 60% [130] - see Fig. 26.

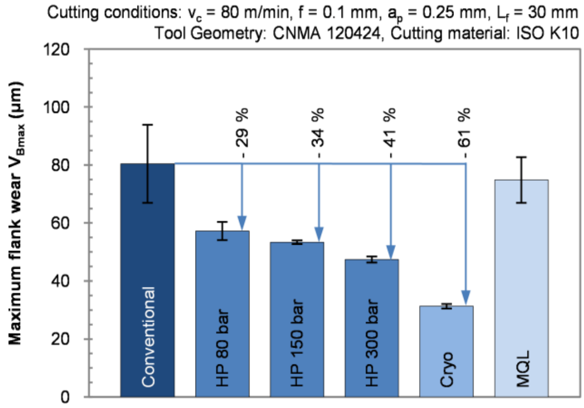

Fig. 26. Tool-wear comparison in conventional, HP (varying rates), MQL and cryogenic machining of *γ−TiAlN* [130].

4.1.6. Machine tool integration

The cryogenic machining process involves jetting a small quantity of LN_2 onto the rake face of the cutting tool insert during the cutting process. LN_2 is either transported from a bulk tank outside the building or from a pressurized cylinder close to the machine through vacuum jacketed lines. The control box, integrated with the machine controller, would signal the LN_2 flow on demand, through flexible lines, to specifically designed nozzles either integrated into the clamp or mounted close to the insert. LN_2 is supplied to all the tools on the turret using a pneumatically actuated back-plunger system that engages and retracts, based on the tool in cut. The nozzle discharges a stable, precise LN_2 jet towards the chip/tool interface. Care is taken not to impinge the cryogenic jet directly onto the workpiece to prevent freezing. In early work, it was shown that the freezing of the workpiece can be realized in a closed cryogenic bath, a general cryogenic flooding or supplying a cryogenic medium on the chip. Further, this effect can be improved by supplying the cryogenic coolant to the cutting edge and rake face, in order to improve chip breaking [195].

To realize an internal supply of the medium for milling or drilling operations, different solutions for cryogenic cooling have been developed. The method by 5ME LLC can be used for cooling, where LN_2 is delivered through tube-in-tube, vacuum-jacketed feed lines from an external bulk storage tank to the cutting tool. Thus, the machine components are kept at ambient temperature [203]. The machine tool builder MAG IAS offered machining centers that are equipped with an internal supply for LN_2. By showing the advantages of productivity, MAG also showed a possible solution for production lines with several machines with a cryogenic process cooling. LN_2 is stored in a tank outside the production hall, and supplied to the machines by vacuum-insulated pipes. Every machine is equipped with a phase separator to supply LN_2 to the cutting tool [204].

4.2. Grinding processes

In grinding processes, the surface cracks in machining of high carbon steels are analyzed [46]. Initiation of surface cracks on dry ground surfaces, which may be attributed to higher temperature and to the susceptibility of this material to phase transformation, has been observed. In wet grinding, the cracking tendency decreased and under cryogenic grinding, it disappeared completely, indicating lower temperatures. Same behavior was seen with the severe cracking on the machined surfaces. Additionally, forces have been analyzed. Cryogenic grinding requires less force and specific energy almost throughout the whole infeed range, which might be attributable to the higher hardness of the work material. Thus, the application of cryogenic grinding has been found to be more beneficial for harder materials throughout the infeed range explored, mainly because of the fractured and sheared mode of material removal, without much rubbing and ploughing [166, 169]. Fig. 27 shows the residual stress relationship with corrosion cracking for both conventional and cryogenic grinding of AISI 304. Results show that while the cryogenic cooling generates the lowest grinding temperature, no significant differences over the specific grinding force components were observed. Cryogenic cooling also led to a reduction in surface roughness of more than 40%. An even higher level of work hardening occurred, a lower level of tensile residual stresses was measured, and better resistance to stress corrosion cracking and pitting corrosion were observed.

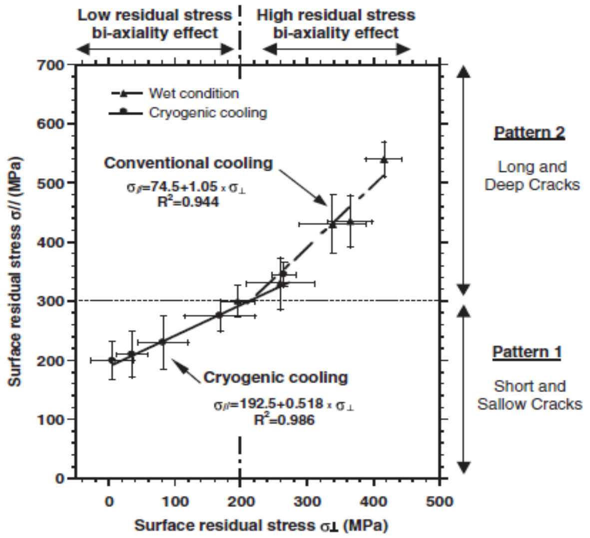

Fig. 27. Relationship between the stress corrosion cracking network and the residual stress distributions generated under conventional and cryogenic grinding [166].

It has also been shown that cryogenic cooling application also shows promising advantages by improving surface quality and topography of the machined components. Paul et al. [46] in their early work found that surface quality with cryogenic grinding increases significantly, in comparison with dry and wet conditions. Similar results were reported subsequently by Venugopal et al. [205]. They show the generation of a smoother surface and improved surface quality in cryogenic grinding.

Grinding is usually applied as a finishing step, which can generate surfaces with advantageous in surface quality and high dimensional accuracy. Grinding processes are characterized by a high level of generated heat, resulting from friction and deformation in the contact zone. Furthermore, the contact area between grinding wheel and workpiece is much larger than in other manufacturing processes, leading to a high amount of heat, which flows into the workpiece. Therefore, it is crucial to avoid thermal damage of the workpiece material by efficient lubricating and cooling systems. Besides dry grinding, conventional flood cooling and MQL, the application of cryogenic cooling is another promising approach to efficiently reduce the temperature in the contact zone during grinding [206-209].

Inasaki et al. [210] in their early work showed the high potential of cryogenic grinding by means of application of high speed jets of cold gas, based on the experience from other machining processes. Especially the high cooling effect combined with the possible avoidance of mineral oil-based metalworking fluids were found to make cryogenic grinding a promising alternative for the future. Over two decades later, several studies on this topic are available, indicating that the technological performance of cryogenic media (LN_2 and CO_2-snow/dry ice) was not overrated. Also, in a very early study on this topic, Chattopadhyay et al. [45] LN_2 as a coolant in face grinding of different steels. Favorable results were obtained regarding the surface quality in terms of surface roughness. Comparable results were presented by Manimaran et al. [211] from cryogenic grinding of stainless steel. They measured and compared the forces, and resulting surface topographies, from grinding with conventional flood cooling, cryogenic cooling (LN_2) and dry grinding. Improved grindability of steels by means of forces, achievable roughness and surface integrity were described by Murthy et al. [212]. For all investigated steels, a reduction of the grinding forces and improved surface roughness were shown in comparison with dry grinding processes, and interestingly, the microhardness was slightly increased for micro-alloyed and low alloyed steels, but for Hadfield steel, a drop of the microhardness on the surface and subsurface layers was observed in cryogenic grinding. Paul and Chattopadhyay [48] compared the temperature in the contact zone, the grinding forces, and the specific energy in cryogenic grinding of steels with the results from dry grinding and grinding with soluble oil. In the cryogenic grinding experiments, the temperature in the contact zone measured by thermocouples was reduced significantly compared to conventional flood cooling and especially dry grinding. Also, the specific energy and the forces were found to be lower when using LN_2 as a coolant. The results show the high potential to avoid thermal damages in complex grinding operations. This result was supported by residual stress measurements indicating a shift of the residual stresses at the surface by more than 300 MPa into the compressive area.

Hoffmeister and Maiz [213], and subsequently Maiz [214], applied LN_2 in varying supply conditions such as the flow rate and the nozzle position. They were able to show that the heat flux into the workpiece is considerably reduced by cryogenic cooling leading to lower temperatures in the contact zone. Additionally, the positive effects of the application of LN_2 with varied flow rate on tool-wear were presented. These results are consistent with the findings of Reddy and Ghosh [215]. In face grinding experiments, they compared the G-ratios for different cooling strategies indicating the lowest wear rates for cryogenic grinding. As a drawback of cryogenic grinding, they found a considerable increase in the required spindle power when LN_2 was applied.

The high potential of LN_2 to reduce the workpiece temperature during, and especially immediately after the grinding process, was used by Nguyen et al. [216] to improve the effects of grind-hardening. In grind-hardening, the high workpiece temperatures generated in grinding processes are utilized to perform a short-term austenitization of the surface and subsurface layers [217]. Within a few seconds, self-quenching or the quick reduction of the workpiece temperature by coolants, it leads to a martensitic transformation during grinding of steels in an initially soft state. Nguyen et al. [216] applied LN_2 to efficiently cool down the workpiece temperature behind the contact zone. The resulting surface integrity was favorable in terms of compressive residual stresses, low roughness and high hardness. Subsequently, Nguyen and Zhang [218] pursued their attempt to show the grind-hardening effect by comparing the surface and subsurface properties after grind-hardening with varied cooling strategies.

The combination of oil mist for lubricating purposes, with *CO_2*-snow for efficient cooling, was analyzed by Garcia et al. (2013). The flow rate, the diameter of the CO_2-snow-nozzle, as well as its position, were varied to identify the parameters that lead to the most efficient cooling and lubrication. Compared to conventional cooling with water-based metalworking fluids, especially an increase of the G-ratio was obtained resulting from the combination of CO_2-snow-peening and MQL – see Fig. 28.

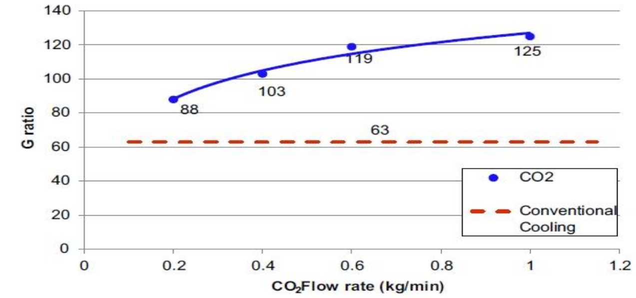

Fig. 28. G-ratios in conventional grinding and grinding-assisted by *CO_2*-snow and MQL at varying flow rates (Garcia et al., 2013)

Considerably reduced grinding forces were also observed by Lee et al. [219], who found that grinding with cooled-air air at −20°C leads to a reduction the normal and tangential grinding forces by 69.6% and 72.8%, respectively, compared to dry grinding. A lower wear rate of the grinding wheel was another positive result of the application of cooled-air.

Further attempts to utilize cryogenic media to reduce the thermal load in grinding processes abstain from a direct supply of the contact zone with the media. Oliveira et al. [220] used the low temperatures achievable by the application of LN_2 to precool a workpiece and combined this step with subsequent dry grinding. They were able to avoid thermal damage and obtained superior surface roughness after precooled dry grinding compared to conventional flood cooling. Tsai and Hocheng [9] in their early work analyzed the effects of using a pre-cooled magnetic chuck for precision grinding in mold and die manufacturing.

More recently, another interesting approach for cryogenic abrasive manufacturing processes was presented by Karpuschewski et al. [221]. The authors applied water-ice particles with temperatures down to 120°C to abrasively deburred workpieces made of steel and polyethylene. They showed correlations among the temperatures of the water-ice, its hardness and the efficiency of deburring.

In summary, the application of cryogenic media has generally proven its potential to increase productivity or the surface integrity of ground surfaces. However, the mechanisms leading to the advantageous effects still have to be analyzed in a systematic way. As an example, it was not yet discussed, if the low temperatures lead to a noticeable shrinkage of steel workpiece, and thereby to a reduced effective depth of cut. This would at least contribute to the reduction of grinding forces, but also cause problems regarding the dimensional accuracy of the ground components.

The environmental effect of cryogenic grinding in comparison to conventional cooling strategies should always consider the amount of energy required to produce the LN_2. Furthermore the flow rate of LN_2 and the service life of conventional metalworking fluids will significantly influence the result of a comprehensive life-cycle assessment (LCA). One of the greatest challenges of cryogenic grinding is the high costs for the cryogenic media in a total-loss-cooling concept [222].

4.3. Forming processes

As introduced in Section 2.2, for materials with face cube centered structures (fcc), cryogenic cooling can significantly enhance the formability, as can be explained by the effects on the dislocation mechanisms [80]. The advantageous effects of cryogenic boundary conditions on the fracture elongation of specific metals has been well-documented [223]. The focus was specifically on materials with fcc structure that do not undergo a transition from ductile to brittle behaviour at cryogenic temperatures [224].

While the advantageous mechanical properties of some aluminium alloys in terms of fracture elongation and work hardening under cryogenic conditions have been documented in early work more recent test reports stress the material and strain history specificity of the formability influence of cryogenic boundary conditions [225-226]. Schneider et al. [227] performed uni-axial tensile tests on different aluminium alloys as a function of temperature. For specific series temperature reductions were demonstrated to have positive effects on the fracture elongation and ultimate tensile strength, both properties that are relevant for forming purposes. Park et al. [228] investigated the properties of 5000- and 6000 series aluminium under cryogenic conditions and observed the increase of the fracture strain at low temperatures for the 5000 series, in contrast with the findings for the 6000 series for which the increase in fracture strain and UTS for decreasing sample temperatures proved to be much less pronounced. The stress-strain curves for different 5000 and 6000 series alloys at ambient and cryogenic temperature (110 deg. K) illustrate the significant difference in formability increase for both series at low temperature, while the UTS increased substantially for both series. Park et al. [228] also investigated the strain-rate sensitivity of the material properties to a wide interval of strain-rates and observed a strong dependency for the 5000 series for strain-rates between 10^{-4} and 10^{-2} s^{-1}. This sensitivity is clearly higher at low temperatures. For 6000 series alloys, only minor influence of the strain-rate was found.

These results for 5000 series aluminium alloys are in compliance with earlier findings of Park et al. (2015), who also observed a similar strain-rate sensitivity to the fracture strain [229]. The high susceptibility of formability of the 5000 series alloys to reduced temperatures can be explained by a reduced influence of the high magnesium content in these alloys at cryogenic temperatures. While at room temperature the Portevin-Le Chatelier phenomenon is known to strongly influence the plastic strain behaviour of these alloys, limiting their formability and resulting in a negative strain-rate sensitivity, cryogenic temperatures are believed to significantly reduce this dynamic strain aging effect of magnesium, thus resulting in improved formability [230-231].

It should be noted that the formability, referred to in this section, is reflected by the fracture strain levels achievable in simple tensile tests. This approach does not take into account the sensitivity of this property to typical localised necking phenomena, nor does it cover the full limit diagram (bi-axial deformation) range as is typically considered when studying material limits in forming. Obviously work hardening has a significant influence on the necking phenomena that determine the limits in a tensile test approach to formability quantification. When more complex strain paths are applied, the dislocation mechanisms described above do not necessarily contribute in a similar advantageous manner to the underlying forming process. In incremental forming, for example, FCC materials such as *AA1050-H24* and *AA5083-H111* show respectively early failure and equal formability compared to formability levels achievable at room temperature, thus indicating some limits to the industrial applicability of the formability enhancing effects of cryogenic cooling [232].

4.3.1. Cryogenic cooling systems: Materials, machines and tooling

In contrast with cryogenic machining, where the material removal action is localised, in most forming processes strains are introduced simultaneously in large areas of sheet metal workpieces. In consequence cooling of parts in process needs to be assured over considerable areas and dedicated setups are required. In order to assure semi static cryogenic conditions, pre cooling cannot suffice unless the time in process would be extremely low thus avoiding significant conductive heat input into the sheet. Local flushing is likely to result in non-homogeneous, non-static temperature fields that depend on the geometry of the workpiece setup. Related patent applications over the past decennia indicate industrial interest to apply enhanced forming capabilities under cryogenic conditions.

As a prerequisite for forming with appropriate surface quality output, Matsui et al. [233] worked on a lubricant suitable for forming under cryogenic conditions based on hydrocarbons selected from the group consisting of mineral oils, synthetic naphthenes, polybutenes, and poly(mono).alpha.-olefins, and C10-C24 linear or branched fatty alcohols.

Methods to dynamically apply cryogenic coolant to large sheet metal surfaces in support of mass forming operations have not been identified in literature. At KU Leuven several setups were tested for incremental forming under cryogenic conditions. Both systems with unilateral and two-sided contact between the sheets and LN_2 coolant in a semi-closed cavity were tested (Fig. 29) [232].

The effects of cryogenic cooling on the tribological conditions between forming tool and workpiece surface can be significant. Lack of oxygen access to the process environment can result in oxide free surface contacts with increased surface damage and resulting roughness increase as result [232].

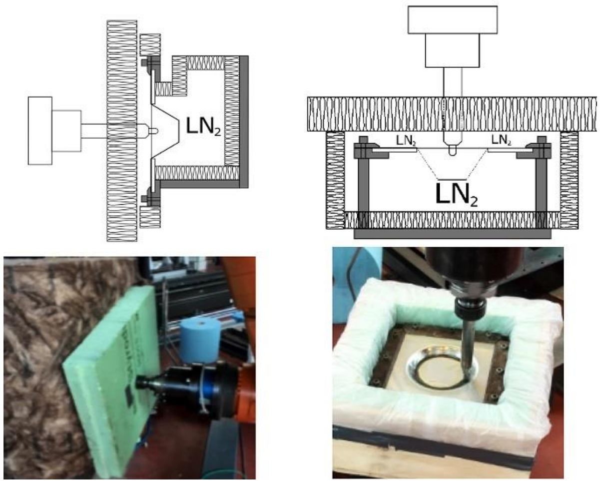

Fig. 29. Single Point Incremental Forming setup with cryogenic cooling facility: vertical setup with single sided *LN_2* (left) and horizontal setup with the workpiece submerged in *LN_2* (right) [232].

A series of industrial reports and patent applications form testimony of efforts to develop industrially relevant applications of cryogenic forming in the 1960's and 1970's. A relevant review is provided in [234] indicating that the targeted advantages of cryogenic forming were improved residual functional material properties rather than improved formability. The authors stress the limited range of materials for which such property improvements could be demonstrated. A clear exception is the strength improvement of stainless steel components formed at cryogenic temperatures. Imgram [235] refers to stretch forming as a suitable process for forming stainless steel, including welded structures, with *AISI 301* as the most responsive material in terms of demonstrated strength improvement. The author describes how this process has been used to produce pressure vessels of rocket motor case configurations. Daigle [236] confirmed that hydrostatic burst pressurization tests conducted at low temperatures (-54ºC) proved the high strength performance of cryogenically formed *AISI 301* rocket motor cases.

Also wire drawing of austenitic stainless steel, with and without martensite formation, is reported to result in substantially higher resulting ultimate tensile strengths at room temperature with typical reported increases of 10% [234].

Selines and Van den Sype [237] describe how solid solution strengthened aluminium alloys from the 1100, 3000, 4000 and 5000 series can be formed cryogenically between -100°C to -200 °C, resulting in improvement of formability when applying work hardening processes prior to cryogenic forming. They also refer to improved dent and scratch resistance through improved hardness.

In a second patent application Selines [238] described a procedure for deep drawing different metals under temperature gradient conditions, with the blank initially cooled to below -50ºC and flanges heated to a higher temperature in order to assure a differential temperature of between 40-150ºC between central area and flanges during forming. He claimed achieving an improved drawability ratio through this strategy.

4.3.3. Product performance enhancement

The surface hardness improvement in aluminium alloys, as observed by Selines [238], was also confirmed in an extensive test program on cryogenically-supported SPIF conducted at KU Leuven for aluminium alloys *AA1050* and *AA5083* [239]. Hardness measurements were taken for a set of truncated cones formed at different temperatures near the wide base and at the narrow top of the cone.

Due to lubrication problems at low temperatures reduced surface quality with high surface roughness could be witnessed. It is likely that superficial damage contributes to early failure under cryogenic forming conditions since, in contrast with most other forming processes, surface damage effects are escalating as result of the repetitive contact nature of SPIF [239].

5. Predictive Model Development for Cryogenic Processes

5.1 Significance of modeling and modeling objectives

Developing analytical, numerical and computational models to predict machining performance and machining-induced surface quality and integrity has been a major challenge during the last few decades [240]. Above all, being able to properly foresee the characteristics of products under different cooling conditions and, more importantly, under cryogenic conditions, significantly reduces the required time to conduct expensive and extensive experiments. Different approaches, for example, empirical, Finite Elements Analysis (FEA), analytical or hybrid models exist to analyse and optimize such complex machining processes. This section summarizes the recent advances on predictive models for cryogenic processes.

5.2 Analytical modelling

For the last three decades, a greater emphasis has been placed on developing analytical models for predicting the trends of some important factors such as cutting force, stress state, strain distribution, heat partitioning, temperature field, etc. [143, 240].

Significant efforts have been made to analytically predict the cooling effect of dry, conventional flood cooling and MQL application, while only few researchers have proposed the need for describing and predicting the cooling effect in cryogenic machining [240-244]. Dhar et al. [65] investigated the role of cryogenic cooling by LN_2 jet on cutting temperature in turning plain carbon steel, and found that cryogenic cooling enables a substantial reduction in the cutting temperature. Ding and Hong [245] applied an analytical procedure for modelling cryogenic turning. They first presented the measurements of heat transfer coefficients for a cryogenically-cooled hard metal insert at different temperatures. They also found high heat transfer values due to intensive contact with the cooling medium based on the kinetic energy of the impinging jet, destroying the insulating vapor layer as it forms.

More recently, Lu [111] proposed a comprehensive approach to determine the heat transfer mechanism of cryogenic machining with flank side LN_2 delivery. By applying the proposed heat transfer modelling approach to the results of the experiments on *AZ31B Mg* alloy, a series of curves for the heat transfer coefficient have been established. Lu [111] also found that a boiling heat transfer pattern has been recognized and distinguished from convection heat transfer.

5.3. Numerical modelling

Over the years, predictive numerical models for fundamental process variables (cutting forces, stress state, strain distribution, temperature field, etc.) in dry machining, as well as the related surface integrity characteristics (affected layer, hardness, grain size, DRX, phase transformation, etc.), have been developed by different researchers [143, 240]. Recently, these numerical models have been also used to predict the above fundamental process variables and surface integrity characteristics when processes are cryogenically-assisted.

Outeiro et al. [171] developed a numerical model to investigate the influence of cutting process parameters and cooling conditions acting on the cutting mechanics and surface integrity produced during machining of *AZ31B-O Mg*. Kheireddine et al. [246] studied the effect of LN_2 cryogenic cooling on the surface integrity of drilled holes in *AZ31B Mg* alloy using an indexable drill. Their model could predict thrust force, torque and surface micro-hardness. They found a small reduction in the cutting forces due to the friction reduction effect caused by the LN_2 while less noticeable influence by cryogenic cooling was noted on the torque. In contrast, an appreciable increase in surface hardness for cryogenically cooled holes, compared with those drilled in the dry condition, has been shown by others, who also developed a numerical model focused on predicting the microstructural changes of *AZ31B Mg* alloy during dry and cryogenic machining [96]. The comparison between initial predictions and experimental data on forces and temperature, as well as chip morphology, was used to calibrate the FEA model by updating the model parameters. Dynamic recrystallization (*DRX*) mechanism of *Mg* alloys under different cutting condition was modelled by developing a user routine based on Zener-Hollomon model. Later, by implementing the same FEA model and following a specific procedure for residual stress prediction, dry and cryogenic machining-induced residual stresses were also predicted [247].

Rotella and Umbrello [95, 97] proposed FEA models and user routines to predict grain size and hardness changes induced during cryogenic machining of *AA 7075-T651* and *Ti6Al4V* alloys. The implemented user subroutines could describe the microstructural changes, phase transformation (*Ti6Al4V*) and dynamic recrystallization occurring during the process, and their influence on the material flow stress and grain size as schematically described in the flow chart of Fig. 30.

In particular, the implemented user routines systematically reproduces the phenomenon of dynamic recrystallization by tracking the deformation and thermal conditions and, consequently, predicting the grain size. It has been clarified that in *SPD* processes recrystallized grain decreases monotonously with increasing Zener–Hollomon parameter,

$$Z = \dot{\varepsilon} \times exp(Q/RT) \qquad (1)$$

where $\dot{\varepsilon}$ is the strain-rate, Q is the activation energy of high-temperature deformation, R is the gas constant and T is absolute temperature. Thus, a finer grain size can be obtained by deformation under higher Z conditions, i.e., at a lower temperature and a higher strain-rate.

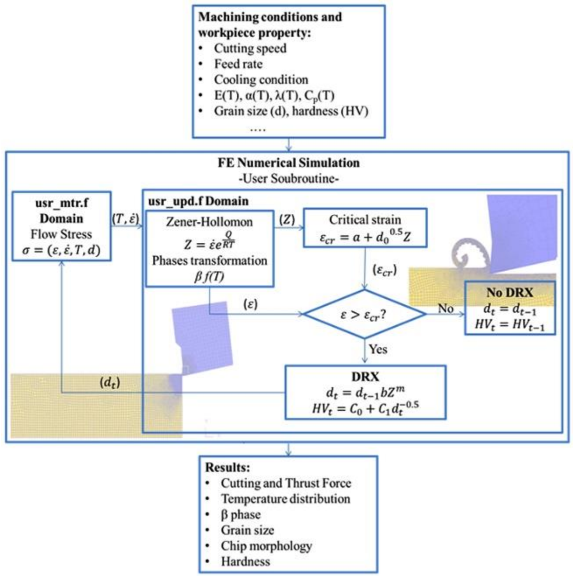

Fig. 30. FE strategy to predict the grain size and hardness variation during *SPD* processes [97].

These phenomena are more relevant when *SPD* processes take place under cryogenic cooling conditions, and they can be numerically inspected by FEA simulation as shown in Fig. 31.

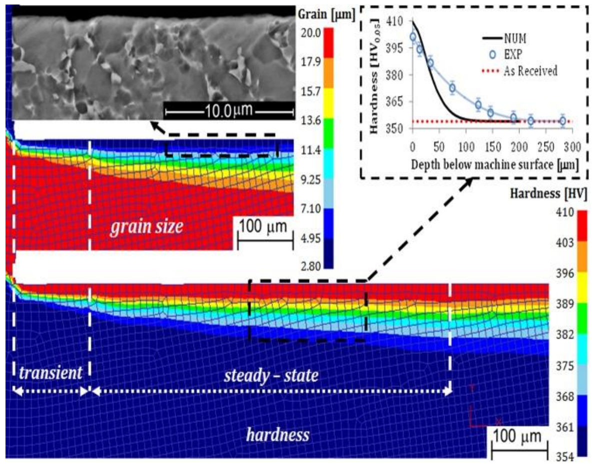

Fig. 31. Predicted and measured grain size and hardness on cryogenically-machined *Ti6Al4V* workpiece at 70 m/min cutting speed, and 0.1 mm/rev feed rate [97].

The effect of cryogenic cooling is even more profound when machining materials sensitive to thermal conditions such as *Ti6Al4V*. In such *Ti* alloy, also the *b* volume fraction is driven by thermal conditions during machining processes since, according to Kim et al (2011), it can be expressed as %:

$$b = a \times b \times exp(cT) \qquad (2)$$

where *a*, *b* and *c* are three material constants. Therefore, cryogenic cooling during machining processes deeply influences the *b* volume fraction.

Recently, Bordin et al. [248] experimentally and numerically investigated the semi-finishing turning of Electron Beam Melted *Ti6Al4V* under dry and cryogenic cooling. Both main cutting forces and temperatures were well predicted when compared with the experimental values. Severe plastic deformation (*SPD*) layer formation was also included in the FEA modelling and the results show that *SPD* thickness increases with increasing cutting speed when cryogenic cooling is applied (Fig. 32).

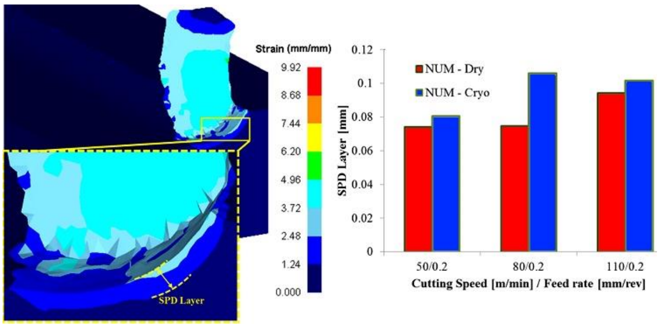

Fig. 32. Position of the SPD layer in the FE model and the predicted average SPD layer thickness [248].

Combining analytical and numerical models can allow creation of hybrid and more powerful science-based models, which can be used to predict industry-relevant process performance measures. In recent study, Dix et al. [11] presented a numerical model for analyzing the heat distribution in the cooled drilling tool, and in the process zone, during high performance drilling of hardened steel *(42CrMo4).* The focus of this work was on the contact zone between the LN_2 and the cooled surface, which were determined by different heat transfer models. The models differ by the occurring gas phase of the boiling LN_2 at contact with surface temperatures above -196°C. The thermal models were verified by experimental temperature measurements at the cooled drill independently from the drilling process. They have been transferred to drilling models and verified by drilling torque and feed force measurements. The drilling models allowed an analysis of the heat distribution in drilling of different tool geometries. Fig. 33 presents the heat distribution for the application of a standard drill with cryogenic cooling.

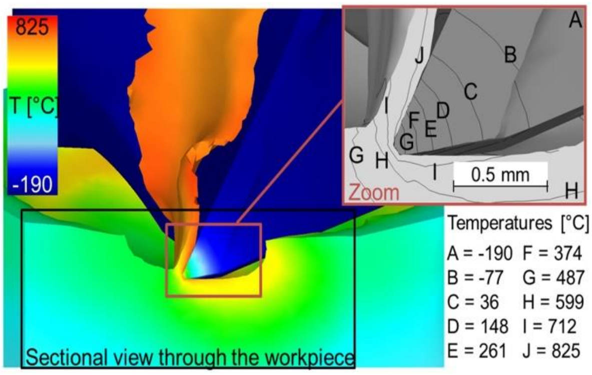

Fig. 33. The chip formation and temperature distribution at the cutting zone during drilling with LN_2 cooling [11].

It became apparent that the cryogenic medium reduces the tool temperatures to -190°C, and very high local temperature gradients occur in the process zone. Different tool geometries were analyzed by using cryogenically cooled drilling. In this context, the geometry of the main cutting edge, in relation to the cooling channel position, becomes an important factor for minimum reached temperatures at the tool tip.

7. Special Manufacturing Applications

7.1. Cryogenic machining of soft elastomers

The realisation of fixturing solutions for freezing workpieces for a range of different elastomer materials to keep them below the glass transition temperature during machining operations have been achieved by a number of authors, namely Mishima et al. [249], Kakinuma et al. [250-251] and Dhokia et al. [252]. This is required as the glass transition temperature in a polymer material is where the material transforms into a rigid or glass like state. At this temperature, cutting forces can be applied in machining operations enabling the CNC machining feasible. Kakinuma et al. [250] used LN_2 to cryogenically cool a poly-dimethyl-siloxane (PDMS) workpiece using a specially designed fixture. They identified that cryogenic machining significantly improved the machinability of PDMS, though they noted that the super cold temperature also gave geometrical inaccuracies in the workpieces produced.

The cryogenic cooling strategy was also adapted on milling using three nozzles placed around the milling tool allowing to cool the workpiece in every feed direction (see Fig. 34 top). The results show a significant improvement in surface integrity with cryogenic assistance (see Fig. 34 bottom left). Chip flow was much better.

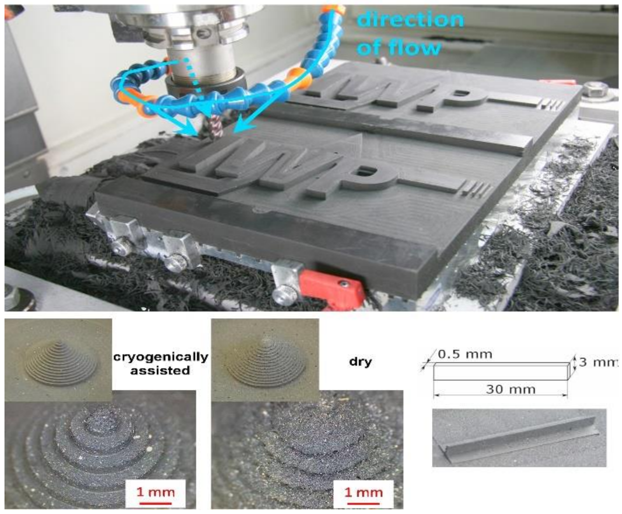

Figure 34. Top: Experimental setup for cryogenic milling of elastomers. Bottom left: Comparison of the results between dry-milled elastomer and cryogenically-assisted milled elastomer. Bottom right: Thin structures down to 0.5 mm thickness can be

This hybrid production process enables to machine very thin elastomer structures up to 0.5 mm due to reduced workpiece deformation (see Fig. 34 bottom right)

The major use of cryogenics in the machining of polymers is in freezing the raw material so as to enable machinability. This is achieved by the characteristic change of polymers from ductile to brittle at low temperatures known as the glass transition temperature. The use of cryogenic temperatures enables the ductility and elongation of the polymer material, giving it the ability to withstand the machining forces without deformation. Dhokia et al. [252] was able to machine a soft elastomer namely ethylene-vinyl acetate (EVA) by freezing the material with LN_2 for milling sculpted surfaces such as shoe soles. This enabled an alternative solution to the expensive and time consuming traditional injection moulding process by directly cryogenically machining the soft elastomer material. A specially designed fixture has been developed to freeze PDMS workpieces for manufacturing micro-fluidic chips by Kakinuma et al. [250]. These micro fluidic chips are normally produced by photolithography and a micro-moulding process. Through the use of cryogenically freezing the material and machining, micro-fluidic chips are generated by the by a micro-milling process. One major issue though is material shrinkage reductions at these cryogenic temperatures and tool run out. Though Kakinuma et al. [250] showed that required surface finish levels were achieved by increasing the spindle speed to

20000 rpm, 1mm/min feed rate and a 10μm depth of cut. With the cryogenic machining of PDMS, Mishima et al. [249] proposed that dimensional inaccuracies can be compensated through the consideration of thermal reduction in the material. This was illustrated by deforming and freezing the part material in order to manufacture different shapes such as bent holes and channel grooves with different shapes as shown in Fig. 35.

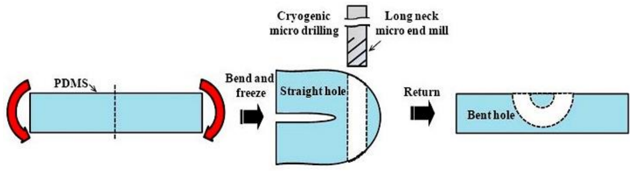

Fig. 35. Pre-deformed bent hole manufacturing process using LN_2 cryogenic freezing [Mishima et al., 2010]

8. Economic Aspects of Cryogenic Processing

Klocke at el. [130] and Pusavec et al. [253] measured the CO_2 and LN_2 flow rates to calculate the costs of cryogenic fluid flows. For the CO_2, five different nozzle scenarios were used, while the consumption of nitrogen has been measured for a single nozzle scenario. The flow rate as shown in Fig. 36 has been measured with weighting procedure.

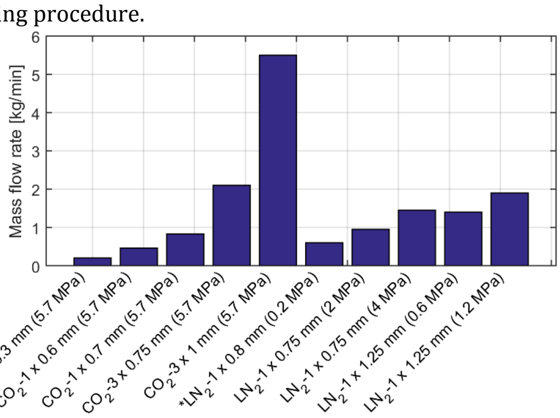

Fig. 36. Flow rates of $\mathbf{LN_2}$ and CO_2 in relation to nozzle sizes (pressure of CO_2 is 5.7MPa and of LN_2 = 0.15 MPa.

Combining cooling lubrication fluid consumption with the tool-life and productivity, the real cost contribution of processes can be calculated for the given case study. Applications showing lower costs of cryogenic machining and high pressure jet assisted machining are analyzed by Pusavec et al. [29] for *Inconel 718.* Results presented in Fig. 37 show the production costs for different machining processes: conventional dry machining, cryogenic and high pressure jet assisted machining. It can be asserted that conventional machining is significantly more expensive than HPJAM or cryo-machining. This trend is even more dominant at higher cutting speeds.

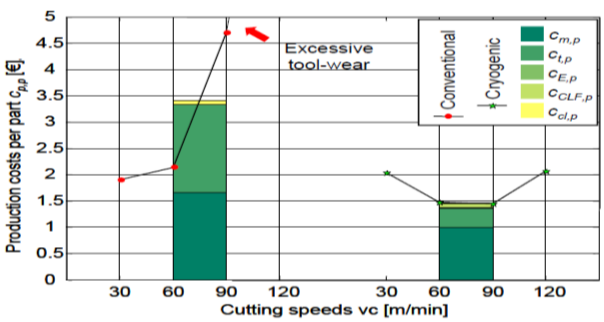

Fig. 37. Production costs comparison for Inconel 718 machining, accounting machining costs, tooling costs, energy costs, cooling lubrication costs and cleaning cost (f = 0.25 mm/rev, a_p = 1.2

Also, at lower cutting speeds, conventional machining can be the cheapest. However, this production rate is not optimal. Therefore, sustainable alternative machining processes, such as HPJAM or cryo-machining, should be used when high efficiency and high productivity of difficult to cut materials are required.

Additional example, performed by [198], compares conventional oil emulsion machining with high pressure, CO_2 and LN_2 as alternative machining processes. A case study was performed on Austenitic stainless steel *X5CrNi18-10.* From the results it can be seen that compared to conventional machining, high pressure prolongs the tool-life by 200% for CO_2 and 100% for LN_2. On other words, with high pressure three times and in CO_2/LN_2 two times less tools will be used. In terms of time, for three minutes of conventional flood-cooled machining, in this case study, tooling costs are significantly higher than costs of the machining with LN_2 or CO_2.

Lu [111] emphasized that economics of cryogenic machining is directly related to the flow rate and the machining performance benefits from its usage. Thus, to achieve a truly sustainable condition, cryogenic coolant should be applied similar to the liquid application in machining with MQL in near-dry machining.

9. Summary and Future Direction

This paper presents a summary of the state-of-the-art in cryogenic processing of materials focusing on processes such as machining, forming, grinding and burnishing. Underpinning science-based process mechanics involving material performance and tribological and thermo-mechanical interactions are described for cryogenic processing. This is followed by a discussion on the influence of such cryogenic processing methods on surface integrity characteristics and the product performance, particularly emphasizing the wear and corrosion resistance and fatigue life through performance characteristics such as grain refinement, hardness improvement and the induced compressive residual stresses resulting from cryogenic processing.

Operational performance of CO_2 and LN_2 based cryogenic systems are then discussed and compared for their effectiveness and limitations against the methods such as traditional flood cooled and high pressure-assisted machining and MQL in terms of achievable machining performance measures such as tool-wear/tool-life, surface roughness, cutting power, chip control, etc. Machine tool integration methods and available cryogenic coolant delivery systems are then briefly discussed.

Optimization methods for cryogenic applications in machining are presented. Analytical and numerical predictive performance modelling efforts are then described. Finally, economic, environmental, safety and health aspects of cryogenic applications are briefly presented.

Based on the findings presented in this paper, cryogenic processing has emerged as novel sustainable processes, offering new opportunities for producing functionally-superior products. Effectiveness of such processes depends heavily on significant progress being made towards achieving optimal performance. The key area for future research is developing improved material/process performance predictive models.

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References

[1] Scurlock RG (1990) A Matter of Degrees: A Brief History of Cryogenics. Cryogenics 30(6): 483-500.
[2] Gunston B (2009) Cryogenic. Cambridge Aerospace Dictionary (2nd Edition). Cambridge University Press.
[3] Reitz G (1919) (Add this reference here)
[4] Doody RD, *Cold Cylinder Assembly for Cryogenic Refrigerator.* US Patent 3969907.
[5] *ASHRAE Handbook Fundamentals* (2010).
[6] Abelle E, Schramm B (2008) Using PCD for machining CGI with a CO2 coolant system. *Production Engineering* 2: 165-169.
[7] De Chiffre L, Andreasen JL, Lagerberg S, Thesken IB (2007) Performance Testing of Cryogenic CO2 as Cutting Fluid in Parting/Grooving and Threading Austenitic Stainless Steel. *CIRP Annals - Manufacturing Technology* 56: 101-104.
[8] Machai C, Biermann D (2011) Machining of beta-titanium-alloy Ti-10V-2Fe-3Al under cryogenic conditions - Cooling with carbon dioxide snow. *Journal of Materials Processing Technology* 211(6): 1175–1183.
[9] Tsai HH, 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: 177-184.
[10] Yalcin B, Ozgur A, Koru M (2009) The Effects of Various Cooling Strategies on Surface Roughness and Tool Wear during Soft Materials Milling. *Materials & Design* 30, 896-899.
[11] Dix M, Wertheim R, Schmidt G, Hochmuth C, (2014) Modeling of Drilling Assisted by Cryogenic Cooling for Higher Efficiency. *CIRP Annals - Manufacturing Technology* 63, 73-76.
[12] Uehara K, Kumagai S (1968) Chip formation, Surface Roughness and Cutting Force in Cryogenic Machining. *Annals of CIRP* 17(1): 409-416.
[13] Dillon Jr OW, De Angelis RJ, Lu, WY, Gunasekera, JS, Deno JA (1990) The Effects of Temperatures on the Machining of Metals. *J. Materials Shaping Technology* 8:23-29.
[14] Hong SY, Ding Y (2001) Cooling Approaches and Cutting Temperatures in Cryogenic Machining of Ti-6Al-4V. *International Journal of Machine Tools & Manufacture* 41: 1417-1437.
[15] Hong SY, Zhao Z (1999) Thermal Aspects, Material Considerations and Cooling Strategies in Cryogenic Machining. *Clean Technologies and Environmental Policy* 1(2): 107-116.
[16] Byers JP (2006) Metaworking Fluids, Second Edition, CRC Press, 2006.
[17] Shaw MC (1959) On the Action of Cutting Fluids at Low Speeds, *Wear* 2(3): 217-227.
[18] Cassin C, Boothroyd G (1965) Lubricating Action of Cutting Fluids, *J. Mechanical Engineering Science* 7(1): 67-81.
[19] De Chiffre, L (1988) Function of Cutting Fluids in Machining. *Lubrication Engineering* 44: 514-518.
[20] Hong SY (2006) Lubrication mechanisms of LN_2 in Ecological Cryogenic Machining. *Machining Science and Technology* 10(1):133-155.
[21] El Baradie M (1996). Cutting Fluids: Part I. Characterisation. *Journal of Materials Processing Technology* 56, 786-797.
[22] Adler DP,. Hii, WWS, Michalek DJ, Sutherland JW (2006) Examining the Role of Cutting Fluids and Efforts to Address Associated Environmental/Health Concerns. *Machining Science and Technology* 10(1): 23-58.
[23] Shokrani A, Dhokia V, Newman ST (2012) Environmentally Conscious Machining of Difficult-to-machine Materials with regard to Cutting Fluids. *International Journal of Machine Tools and Manufacture* 57: 83-101.
[24] Shokrani A, Dhokia V, Newman ST (2014) A Techno-Health Study of the Use of Cutting Fluids and Future Alternatives. *24th International Conference on Flexible Automation and Intelligent Manufacturing*, San Antonio, Texas.
[25] Brinksmeier E, Meyer D, Huessman-Cordes AG, Hermann, C (2015) Metalworking Fluids - Mechanisms and Performance, *CIRP Annals - Manufacturing Technology* 64(2),
[26] Klocke and Eisenblatter G (1997) Dry Cutting, *CIRP Annals – Manufacturing Technology* 46(2): 519-526.
[27] Byrne G, Dornfeld DA, Denhkena, B (2003) Advancing Cutting Technology. *CIRP Annals - Manufacturing Technology* 52(2): 483-507.
[28] Weinert K, Inasaki I, Sutherland JW, Wakabayashi T (2004) Dry Machining and Minimum Quantity Lubrication. *CIRP Annals – Manufacturing Technology* 53(2): 511-537.
[29] Pusavec F, Stoic A, Kopac J (2010) Sustainable Machining Process - Myth or Reality. *Strojarstvo* 52 (2): 197-204.
[30] Jayal, AD, Badurdeen F, Dillon Jr OW, Jawahir IS (2010) Sustainable Manufacturing: Modeling and Optimization Challenges at the Product, Process and System Levels. *CIRP Journal of Manufacturing Science and Technology* 2: 144-152.
[31] Clapp RW, Jacobs MM, Loechler EL (2008) Environmental and Occupational Causes of Cancer: New Evidence 2005-2007. Rev. Environmental Health 23(1): 1-38.
[32] Malloy EJ, Miller, KL, Eisen EA (2007) Rectal Cancer and Exposure to Metalworking Fluids in the Automobile Manufacturing Industry. *Occupational and environmental medicine* 64: 244-249.
[33] De Joode BVW, Bierman E, Brouwer D, Spithoven J, Kromhout H (2005) An Assessment of Dermal Exposure to Semi-Synthetic Metal Working Fluids by Different Methods to Group Workers for an Epidemiological Study on Dermatitis. *Occupational and environmental medicine* 62, 633-641.
[34] Shokrani A, Dhokia V, Munoz-Escalona P, Newman ST (2013) State-of-the-art Cryogenic Machining and Processing. *International Journal of Computer Integrated Manufacturing* 26: 616-648.
[35] Hong SY, Ding Y, Jeong W (2002) Experimental Evaluation of Friction Coefficient and Liquid Nitrogen Lubrication Effect in Cryogenic Machining. *Machining Science and Technology* 6: 235-250.
[37] Hong SY, Broomer M (2000) Economical and Ecological Cryogenic Machining of AISI 304 Austenitic Stainless Steel. *Clean Products and Processes* 2(3): 157–166.
[38] Shokrani A, Dhokia V, Newman ST, Imani-Asrai R (2012) An Initial Study of the Effect of Using Liquid Nitrogen Coolant on the Surface Roughness of Inconel 718 Nickel-Based Alloy in CNC Milling. *Procedia CIRP* 3: 121-125.
[39] Rotella G, Umbrello D, Dillon Jr OW, Jawahir IS (2012) Evaluation of Process Performance for Sustainable Hard Machining. *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 6(6): 989-998.
[40] Kaynak, Y, Lu T, Jawahir IS (2014) Cryogenic Machining-Induced Surface Integrity: A Review and Comparison with Dry, MQL, and Flood-Cooled Machining. *Machining Science and Technology* 18:149-198.
[41] Pu Z, Outeiro JC, Batista AC, Dillon Jr OW, Puleo DA, Jawahir IS (2012a) Enhanced surface integrity of AZ31B MQ alloy by cryogenic machining towards functional performance of machined components. *International Journal of Machine Tools & Manufacture* 56: 17-27.
[42] Pu Z, Song GL, Yang S, Outeiro JC, Dillon Jr OW, Puleo DA, Jawahir IS (2012b) Grain Refined and Basal Textured Surface Produced by Burnishing for Improved Corrosion Performance of AZ31B Mg Alloy. *Corrosion Science* 57: 192-201.
[43] Umbrello D, Micari F, Jawahir IS (2012) The Effects of Cryogenic Cooling on Surface Integrity in Hard Machining: A Comparison with Dry Machining. *CIRP Annals - Manufacturing Technology* 61: 103-106.
[44] Yang S, Umbrello, D, Dillon Jr OW, Puleo DA, Jawahir IS (2015) Cryogenic Cooling Effect on Surface and Modifications in Burnishing of Co-Cr-Mo Biomedical Alloy. *Journal of Materials Processing Technology* 217: 211-221.
[45] Chattopadhyay AB, Bose A, Chattopadhyay AK (1985) Improvements in Grinding Steels by Cryogenic Cooling. *Precision Engineering* 7(2): 93-98.
[46] Paul S, Bandyopadhyay PP, Chattopadhyay AB (1993) Effects of Cryo-cooling in Grinding Steels. *Journal of Materials Processing Technology* 37: 791-800.
[47] Paul S, Dhar NR, Chattopadhyay AB (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: 44-48.
[48] Paul S, Chattopadhyay AB (1995) Effects of Cryogenic Cooling by Liquid Nitrogen Jet on Forces, Temperature and Residual Stresses in Grinding Steels. *Cryogenics* 35: 515-523.
[49] Paul S, Chattopadhyay AB (1996) The Effect of Cryogenic Cooling on Grinding Forces. *Int. J. of Machine Tools and Manufacture* 36(1): 63-72.
[50] Paul S, Chattopadhyay AB (2006) Environmentally Conscious Machining and Grinding with Cryogenic Cooling. *Machining Science and Technology* 10(1): 87-131.
[51] Hong SY, Ding Y (1998) Improvement of Chip Breaking in Machining Low Carbon Steel by Cryogenically Precooling the Workpiece. *Journal of Manufacturing Science and Engineering* 120(1): 76–83. 1
[52] Hong SY, Ding Y, Ekkens RG (1999) Improving Low Carbon Steel Chip Breakability by Cryogenic Chip Cooling. *International Journal of Machine Tools & Manufacture* 39 (7): 1065–1085.
[53] Hong SY, Markus I, Jeong W (2001) New Cooling Approach and Tool Life Improvement in Cryogenic Machining of Titanium Alloy Ti-6Al-4V. *International Journal of Machine Tools & Manufacture* 41(15): 2245–2260.
[54] Hong SY, Ding Y, Jeong W (2001) Friction and Cutting Forces in Cryogenic Machining of Ti-6Al-4V. *International Journal of Machine Tools & Manufacture* 41:2271-2285.
[55] Hong SY (2001) Economical and Ecological Cryogenic Machining. *Journal of Manufacturing Science and Engineering* 123(2): 331-338.
[56] Hong SY, Ding Y (2001b) Micro-temperature Manipulation in Cryogenic Machining of Low Carbon Steel. *J Materials Processing Technology* 116: 22-30.
[57] Wang ZY, Rajurkar KP, Fan J (1996) Turning Ti-6Al-4V Alloy with Cryogenic Cooling. *Transactions-North American Manuf Research Institution of SME*: 3–8.
[58] Wang ZY, Rajurkar KP (2002) Cryogenic Machining of Titanium. *Journal of Manufacturing processes* 4(2): 122-127.
[59] Wang ZY, Rajurkar KP (1997) Wear of CBN tool in Turning of Silicon Nitride with Cryogenic Cooling. *Intl J Machine Tools & Manufacture* 37(3): 319–326.
[60] Wang ZY, Rajurkar KP (2000) Cryogenic Machining of Hard-to-cut Materials. *Wear* 239 (2): 168-175.
[61] Yildiz Y, Nalbant M (2008) A Review of Cryogenic Cooling in Machining Processes. *International Journal of Machine Tools & Manufacture* 48: 947-964.
[62] Busch K, Hochmuth C, Pause B, Stoll A, Wertheim R (2015) Investigation of Cooling and Lubrication Strategies for Machining High-Temperature Alloys. *48th CIRP Conference on Manufacturing Systems - CIRP CMS 2015*, Ischia, Italy, in Press.
[63] Bermingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS (2011) New Observations on Tool life, Cutting Forces and Chip Morphology in Cryogenic Machining of Ti6Al4V. *International Journal of Machine Tools & Manufacture*, 51, pp. 500-511.
[64] Bermingham MJ, Palanisamy S, Kent D, Dargusch MS (2012) A Comparison of Cryogenic and High Pressure Emulsion Cooling Technologies on Tool Life and Chip Morphology in Ti6Al4V. *Journal of Materials Processing Technology* 212: 752-765.
[65] Dhar NR, Paul S, Chattopadhyay AB (2002c) Role of Cryogenic Cooling on Cutting Temperature in Turning Steel. *Transactions of ASME-Journal of Manufacturing Science and Engineering* 124: 146–154.
[66] Dhar NR, 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 & Manufacture* 47: 754-759.
[67] Jawahir IS, Pu Z, Yang S, Rotella G, Kaynak Y, Lu T, Deshpande A, Umbrello D, Dillon Jr OW (2012) Cryogenic Processing of Materials for Enhanced Product Life, Performance and Sustainability. *15th International Conference on Advances in Materials and Processing Technologies*: 1–11.
[68] Reitz W, Pendray J (2001) Cryoprocessing of Materials: A Review of Current Status. *Materials and Manufacturing Processes* 16(6): 829–840.

[69] Patil PI, Tated RG (2012) Comparison of Effects of Cryogenic Treatment on Different Types of Steels: A Review. *International Journal of Computer Applications* 9: 10–29.
[70] Diekman F, Papp R (2009): Cold Facts about Cryogenic Processing. *Heat Treating Progress* 9(6): 33–36.
[71] Schatt W, Simmchen E, Zouhar G (2009) Konstruktionswerkstoffe des Maschinen- und Anlagenbaues. 5th ed.: Wiley.
[72] Knopp L (1970) Werkstoffverhalten unter mechanischer Beanspruchung bei hohen und tiefen Temperaturen. *Chemie-Ing.-Techn.* 42 (11): 743–750.
[73] Bensely A, Prabhakaran A, Mohan Lal D, Nagarajan G (2005) Enhancing The Wear Resistance of Case Carburized Steel (En 353) by Cryogenic Treatment. *Cryogenics* 45(12): 747–754.
[74] Singh PJ, Mannan SL, Jayakumar T, Achar DRG (2005) Fatigue Life Extension of Notches in AISI 304L Weldments using Deep Cryogenic Treatment. *Engineering Failure Analysis* 12(2), pp. 263–271.
[75] Harish, S., Bensely, A., Lal, D.M., Rajadurai, A. and Lenkey, G.B., 2009. Microstructural study of cryogenically treated En 31 bearing steel. Journal of materials processing technology, 209:7,3351-3357.
[76] Sri Siva R, Mohan Lal D, Jaswin MA (2012) Optimization of Deep Cryogenic Treatment Process for 100Cr6 Bearing Steel Using the Grey-Taguchi Method. *Tribology Transactions* 55(6): 854-862.
[77] Bensely A, Venkatesh S, Mohan Lal D, Nagarajan G, Rajadurai A, Junik K (2008) Effect of Cryogenic Treatment on Distribution of Residual Stress in Case Carburized En 353 Steel. *Materials Science and Engineering: A* 479(1-2): 229–235.
[78] Mahlo T, Waning G (2010) Kältebehandlung von Stählen. Technologie, Verfahren und Anlagen (The Linde Group).
[79] Fritsch S, Scholze M, Wagner MFX (2012) Cryogenic Forming of AA7075 by Equal-Channel Angular Pressing. *Mat.-wiss. u. Werkstofftech.* 43(7): 561–566.
[80] Kula EB, DeSisto TS (1966) Plastic Behaviour of Metals at Cryogenic Temperatures. *Am. Soc. Testing Mats.*: 3–31.
[81] Rösler J, Harders H, Bäker M (2006) Mechanisches Verhalten der Werkstoffe. 2nd ed. Wiesbaden: Teubner.
[82] Macherauch E, Vöhringer O (1978) Das Verhalten metallischer Werkstoffe unter mechanischer Beanspruchung. *Z. Werkstofftechn*. 9: 370–391.
[83] Lee YB, Shin DH, Park KT, Nam WJ (2004) Effect of Annealing Temperature on Microstructures and Mechanical Properties of a 5083 Al Alloy Deformed at Cryogenic Temperature. *Scripta Materialia* 51(4): 355–359.
[84] Meng F, Tagashira K, Azuma R, Sohma, H (1994) Role of Eta-carbide Precipitation's in the Wear Resistance Improvements of Fe-12-Cr-Mo-V-1.4C Tool Steel by Cryogenic Treatment. ISIJ International 34 (20): 205–210.
[85] Candane D, Alagumurthi N, Palaniradja K (2013) Effect of Cryogenic Treatment on Microstructure and Wear Characteristics of AISI M35 HSS. *International Journal of Materials Science and Applications* 2(2): 56–65.
[86] Paulin P (1993) Frozen Gears. *Gear Technology* March/April: 26–29.
[87] Gill SS, Singh J, Singh H, Singh R (2012) Metallurgical and Mechanical Characteristics of Cryogenically Treated Tungsten Carbide (WC–Co). *International Journal of Advanced Manufacturing Technology* 58(1-4): 119–131
[88] Thornton R, Slatter T, Lewis R (2014) Effects of Cryogenic Treatment on the Wear Development of H13A Tungsten Carbide Inserts when Machining AISI 1045 Steel. *Production Engineering* 8(3): 355–364.
[89] Machai C, Abrahams H, Biermann D (2012) Machinability of β-Titanium Alloy Ti-10V-2Fe-3Al with Different Microstructures. *TMS, Supplemental Proceedings: Materials Processing and Interfaces* 1.
[90] Klocke F, Kramer A, Sangermann H, Lung D (2012) Thermo-mechanical Tool Load during High Performance Cutting of Hard to Cut Materials. *Procedia CIRP* 1:312-317.
[91] Van Luttervelt CA, Childs THC, Jawahir IS, Klocke F, Venuvinod PK (1998) Present Situation and Future Trends in Modelling of Machining Operations Progress Report of the CIRP Working Group 'Modelling of Machining Operations'. *Annals of the CIRP* 47(2):587-626.
[92] Childs THC, Mahdi MI, Barrow G (1989) On the Stress Distribution between the Chip and Tool during Metal Turning. *Annals of the CIRP* 38(1):55-58.
[93] Rech J, Arrazola PJ, Claudin C, Courbon C, Pusavec F, Kopac J (2014) Characterisation of Friction and Heat Partition Coeffcients at the Tool-work Material Interface in Cutting. *CIRP Annals – Manufacturing Technology* 62:79-82.
[95] Rotella G, Umbrello D (2014) Finite Element Modeling of Microstructural Changes in Dry and Cryogenic Cutting of Ti6Al4V Alloy. *CIRP Annals – Manufacturing Technology* 63:69-72.
[96] Pu Z, Umbrello D, Dillon Jr OW, Lu T, Puleo DA, Jawahir IS (2014a) Finite Element Modeling of Microstructural Changes in Dry and Cryogenic Machining of AZ31B Magnesium Alloy. *Journal of Manufacturing Processes* 16:335-343.
[97] Rotella G, Umbrello D (2014b) Numerical Simulation of Surface Modification in Dry and Cryogenic Machining of AA7075 alloy. *Procedia CIRP* 13:327-332.
[98] El-Tayeb NSM, Yap TC, Venkatesh VC, Brevern PV (2009) Modeling of Cryogenic Frictional Behaviour of Titanium Alloys Using Response Surface Methodology Approach. *Materials & Design* 30(10):4023-4034.
[99] Courbon C, Pusavec F, Dumont F, Rech J, Kopac J (2013) Tribological Behavior of Ti6Al4V and Inconel 718 under Dry and Cryogenic Conditions – Applications to the Context of Machining with Carbide Tools. *Tribology International* 66:72-82.
[100] Cristino VAM, Rosa PAR, Martins PAF (2010) Cutting under Active and Inert Gas Shields : A Contribution to the Mechanics of Chip Flow. *International Journal of Machine Tools & Manufacture* 50:892-900.
[101] Astakhov VP (2010) Metal Cutting Theory Foundations of Near-Dry (MQL) Machining. *Int J Machining & Machinability of Materials* 7: ½: 1-16.
[102] Woodcraft AL (2007) *An Introduction to Cryogenics.* SUPA institute of Astronomy, Edinburgh University, Blakford Hill, United Kingdom.
[103] Sharma VS, Dogra M, Suri NM (2009) Cooling Techniques for Improved Productivity in Turning. *Int J of Machine Tools & Manufacture* 49: 435–453.
[104] Zuckerman N, Lior N (2006) Jet Impingement Heat Transfer: Physics, Correlations, and Numerical Modelling. *Advanc.es in Heat Transfer* 39: 565-631.
[105] Chehroudi B, Talley D, Coy E (2002) Visual Characteristics and Initial Growth Rates of Round Cryogenic Jets at Subcritical and Supercritical Pressures. *Physics of Fluids,* 14 (2): 850-861.
[106] Chehroudi B Talley D, Mayer W, Oschwald M (2003) Understanding Injection into High Pressure Supercritical Environments. *5th Int. Conf. Liquid Rocket Propellant,* Chattanooga, TN, USA 27-30.
[107] Zelinski P (2011) The 400° Difference-Cryogenic Machining. *Modern Machine Shop* (http://www.mmsonline.com/articles/the-400-difference)
[108] Barron RF, Stanley RS, (1994) Film Boiling Under an Impinging Cryogenic Jet. *Advances in Cryogenic Engineering.* 9: 1769-1777.
[109] Dreitser GA (2003) Modern Problems of Cryogenic Heat Transfer and Its Enhancement. *Low Temperature and Cryogenic Refrigeration,* S. Kaka, et al. (eds.), 201-220.
[110] Haustein HD. Tebrügge G. Rohlfs, W, Kneer R (2012) Local Heat Transfer Coefficient Measurement through a Visibly-Transparent Heater under Jet-Impinge Cooling. *Int J Heat and Mass Transfer* 55: 6410–6424.
[111] Lu T (2014) A Metrics-based Sustainability Assessment of Cryogenic Machining Using Modeling and Optimization of Process Performance. PhD Dissertation, Department of Mechanical Engineering, University of Kentucky.
[112] Elsayed A, Attia MH, Damir A (2016) Computer Fluid Dynamics Analysis for Enhanced Cooling of Cutting Tools in Turning Operation. *LTR-SMM-2016-01,* National Research Council of Canada, NRC, 2016
[113] Collier JG, Thome JR (1994) *Convective Boiling and Condensation.* 3rd ed., Clarendon Press, Oxford.
[114] Dhir VK (1991) Nucleate and Transition Boiling Heat Transfer under Pool and External Flow Conditions. *Int. J, Heat and Fluid Flow* 12:((4): 290-314.
[115] Zhang P, Xu GH, Fu X, Li CR (2011) Confined jet impingement of liquid nitrogen onto different heat transfer surfaces. *Cryogenics* 51: 300–308.
[116] Attia MH, D'Silva NS (1983) Thermal Analysis of the Fuel Bearing Pad in the CANDU Reactor–Prediction of Nucleate Boiling. *Proc. 3rd Multiphase Flow and Heat Transfer Symposium,* T.N. Veziroglue et al. (eds.), Florida, USA, 851-863.
[117] Pusavec F, Courbon C, Rech J, Kopac J, Jawahir IS (2014) An Investigation of the Effect of Nitrogen Phase on Cryogenic Performance and a Case Study on Machining of Inconel718. *Proceedings of the ASME2014 International Manufacturing Science and Engineering Conference*, Detroit, USA, MSEC2014-3992.
[118] Dhokia V., Shokrani A. , Newman, S., 2012. Cryogenic Machining of Carbon Fibre. In: 12th International Conference of the European Society for Precision Engineering & Nanotechnology, 2012-06-04 - 2012-06-08, Stockholm.
[119] Qi S.L, Zhang P, Wang R.Z, Xu, L.X (2007) Flow boiling of liquid nitrogen in miro-tubes: Part 2 : Heat transfer characteristics and critical heat flux. International Journal of Heat and Mass Transfer 50:5017-5030.
[120] Pusavec F, Lu T, Courbon C, Rech J, Aljancic U, Kopac J, Jawahir IS (2016) Analysis of the influence of nitrogen phase and surface heat transfer coefficient on cryogenic machining performance. *Journal of Materials Processing Technology,* Volume 233, 2016, pp. 19-28.
[121] Sun S, Brandt M, Dargusch MS (2010) Machining Ti6AL4V Alloy with Cryogenic Compressed Air cooling. *International Journal of Machine Tools & Manufacture* 50:933-942.
[122] Chorowski M (1999) Combined Thermo-Hydraulic Analysis of a Cryogenic Jet. *Cryogenic Engrg. and Int. Cryogenic Materials Conf.,* Montreal, Canada, 1-8.
[123] Xu P, Yu B, Qiu S, Poh HJ, Mujumdar AS (2010) Turbulent Impinging Jet Heat Transfer Enhancement Due To Intermittent Pulsation. *Int. J. Thermal Sciences* 49: 1247-1252.
[124] Tesar V (2009) Enhancing Impinging Jet Heat or Mass Transfer by Fluidically Generated Flow Pulsation. *Chemical Engineering Research and Design* 87: 181-192.
[125] Pusavec F, Kramar D, Krajnik P, Kopac J (2010) Transitioning to Sustainable Production – Part II: Evaluation of Sustainable Machining Technologies. *Journal of Cleaner Production* 18(12): 1211-1221.
[126] Pu Z, Caruso S, Umbrello D, Dillon Jr OW, Puleo DA, Jawahir IS (2011a) Analysis of Surface Integrity in Dry and Cryogenic Machining of AZ31B Mg Alloy. *Advanced Material Research* 223: 439-448.
[127] Umbrello D (2013) Analysis of the White Layers Formed during Machining of Hardened AISI 52100 Steel under Dry and Cryogenic Cooling Conditions. *International Journal of Advanced Manufacturing Technology* 64: 633-642.
[128] Yang S, Dillon Jr OW, Puleo DA, Jawahir IS (2012) Effect of Cryogenic Burnishing on Surface Integrity Modifications of Co-Cr-Mo Biomedical Alloy. *Journal of Biomedical Materials Research B: Applied Biomaterials* 101B(1): 139-152.
[129] Klocke F, Lung D, Arft M, Priarone PC, Settineri L (2013a) On High-speed Turning of a Third-generation Gamma Titanium Aluminide. *International Journal of Advanced Manufacturing Technology*, 64: 155-163.
[130] Klocke F, Lung D, Kramer A, Cayli T, Sangermann H (2013b) Potential of Modern Lubricoolant Strategies on Cutting Performance. *Key Engineering Materials* (554-557): 2062-2071.
[131] Truesdale SL, Shin YC (2009) Microstructural Analysis and Machinability Improvement of Udimed 720 via Cryogenic Milling. *Machining Science and Technology* 13(1): 1-19.
[132] Grzesik W, Zak K, Prazmowski M, Storch B, Palka T (2012) Effects of Cryogenic Cooling on Surface Layer Characteristics Produced by Hard Turning. *Archives of Materials Science and Engineering* 54(1): 5-12.
[133] Grzesik, W, Zak, K (2013) Producing High Quality hardened Parts using Sequential Hard Turning and Ball Burnishing Operations. *Precision Engineering* 37: 849-855.

[134] Ghosh R, Zurecki Z, Frey HJ (2003) Cryogenic Machining with Brittle Tools and Effects on Tool Life. *Proceedings of ASME International Mechanical Engineering Congress & Exposition*, Washington, D.C., paper nr. IMECE2003-42232.
[135] Dhananchezian M, Kumar MP (2011) Cryogenic Turning of the Ti-6Al-4V Alloy with Modified Cutting Tool Inserts. *Cryogenics* 51: 34-40.
[136] Aramcharoen A, Chuan SK (2014) An Experimental Investigation on Cryogenic Milling of Inconel 718 and Its Sustainability Assessment. *Procedia CIRP* 14: 529-534.
[137] Pusavec F, Hamdi H, Kopac J, Jawahir IS (2011) Surface Integrity in Cryogenic Machining of Nickel Based Alloy—Inconel 718. *Journal of Materials Processing Technology* 211 (4): 773–783.
[138] Kaynak Y, Karaca H, Jawahir IS (2011) Cryogenic machining of NiTi shape memory alloy. *6th Int. Conference and Exhibition on Design and Production of Machines and Dies/Molds*, 23–26 June, Ankara, Turkey, 123–128.
[139] Kaynak Y, Karaca HE, Noebe RD, Jawahir IS (2013): Tool-wear Analysis in Cryogenic Machining of NiTi Shape Memory Alloys: A Comparison of Tool-wear Performance with Dry and MQL Machining. *Wear* 306: 51-63.
[140] Kaynak Y, Karaca HE, Jawahir IS (2015), Cutting speed Dependent Microstructure and Transformation Behavior of *NiTi* Alloy in Dry and Cryogenic Machining", *Journal of Materials Engineering and Performance* 24(1): 452-460.
[141] Kaynak, Y, Robertson SW, Karaca, HE, Jawahir IS (2015) Progressive Tool-wear in Machining of Room-temperature Austenitic NiTi Alloys: The Influence of Cooling/lubricating, Melting, and Heat Treatment Conditions, *J. Materials Processing Technology* 215: 95-104.
[142] Kaynak Y, Karaca HE, Noebe RD, Jawahir IS (2015), The Effect of Active Phase of the Work Material on Machining Performance of a *NiTi* Shape Memory Alloy, *J. Metallurgical and Materials Transactions A,* DOI 10.1007/s1661-015-828-1 (online ISSN 1543-1940)
[143] Jawahir IS, Brinksmeier E, M'Saoubi R, Aspinwall DK, Outeiro JC, Meyer D, Umbrello D, Jayal AD (2011) Surface Integrity in Material Removal Processes: Recent Advances. *CIRP Annals - Manufacturing Technology* 60(2): 603-626.
[144] Gerloff S (2010) Herausforderungen an die spanende Bearbeitung moderner Flugtriebwerkskomponenten. Zerspanen im modernen Produktionsprozess. 05.09.2010.
[145] Hardy MC, Herbert CRJ, Kwong J, Lia W, Axinte DA, Sharman ARC, Encinas-Oropesa, A, Withers PJ (2014) Characterising the Integrity of Machined Surfaces in a Powder Nickel Alloy used in Aircraft Engines. *Procedia CIRP* 13: 411–416.
[146] Bergmann S (2012) Triebwerksteilefertigung – Herausforderungen im Umgang mit Titan- und Nickelbauteilen. Zerspanen im modernen Produktionsprozess. 05.09.2010.
[147] Thornton R, Slatter T, Jones AH, Lewis R (2011) The Effects of Cryogenic Processing on the Wear Resistance of Grey Cast Iron Brake Discs. *Wear* 271(9-10): 2386–2395.
[148] Yang S, Puleo DA, Dillon Jr OW, Jawahir IS (2011) Surface Layer Modifications in Co-Cr-Mo Biomedical Alloy from Cryogenic Burnishing. *Procedia Engineering* 19: 383–388.
[149] Caudill J, Huang B, Arvin C, Schoop J, Meyer K, Jawahir IS (2014) Enhancing the Surface Integrity of Ti-6Al-4V Alloy through Cryogenic Burnishing. *Procedia CIRP* 13: 243–248.
[150] Meyer D, Brinksmeier E, Hoffmann F (2011) Surface Hardening by Cryogenic Deep Rolling. *Procedia Engineering* 19: 258–263.
[151] Dhar NR, Paul S, Chattopadhyay AB (2002a) The Influence of Cryogenic Cooling on Tool Wear, Dimensional Accuracy and Surface Finish in Turning AISI 1040 and E4340C Steels. *Wear* 249:932-942.
[152] Dhar NR, Paul S, Chattopadhyay AB (2002b) Machining of AISI 4140 Steel under Cryogenic Cooling - Tool Wear, Surface Roughness and Dimensional Deviation. *Journal of Materials Processing Technology* 123: 483-489.
[153] Bicek M, Dumont F, Courbon C, Pusavec F, Rech J, Kopac J (2012) Cryogenic Machining as an Alternative Turning Process of Normalized and Hardened AISI52100 Bearing Steel. *Journal of Materials Processing Technology* 212: 2609–2618.
[154] Evans C and Byan JB (1991) Cryogenic Diamond Turning of Stainless Steel. *CIRP Annals – Manufacturing Technology* 40(1): 571-575.

[155] Pusavec F, Deshpande A, Yang S, M'Saoubi R, Kopac J, Jawahir IS (2014b) Sustainable Machining of High Temperature Nickel Alloy – Inconel 718: Part 1 – Predictive Performance Models. *Journal of Cleaner Production* 81: 255-269.
[156] Pusavec F, Deshpande A, Yang S, M'Saoubi R, Kopac J, Jawahir IS (2015) Sustainable Machining of High Temperature Nickel Alloy – Inconel 718: Part 2 – Chip Breakability and Optimization. *Journal of Cleaner Production* 87: 941-952.
[157] Xia T, Kaynak Y, Jawahir IS (2016) Cryogenic Cooling-induced Process Performance and Surface Integrity in Drilling CFRP Composite Material. *Int. J. Advanced Manufacturing Technology* 82(1-4): 605-616.
[158] Schoop, J., F. Ambrosy, F. Zanger, V. Schulze, T.J. Balk and I.S. Jawahir (2015). "Cryogenic Machining of Porous Tungsten for Enhanced Surface Integrity." Journal of Materials Processing Technology. 229: 614-621
[159] Schoop, J., F. Ambrosy, F. Zanger, V. Schulze, T.J. Balk and I.S. Jawahir (2015). "Increased Surface Integrity in Porous Tungsten from Cryogenic Machining with Cermet Cutting Tool." Materials and Manufacturing Processes. 31:7; 823-831
[160] Schoop, J., M. Effgen, et al. (2013). The Effects of Depth of Cut and Precooling on Surface Porosity from Cryogenic Machining of Porous Tungsten. Procedia CIRP 8: 357-362
[161] Schoop, J, I.S. Jawahir, T.J. Balk, (2015) Size effects in finish machining of porous powdered metal for engineered surface quality, Precision Engineering, 44: 180-191
[162] Meyers MA, Vöhringer O, Lubarda VA (2001) The Onset of Twinning in Metals: A Constitutive Description. *Acta Materialia* 49 (19): 4025–4039.
[163] Mecking H, Kocks UF (1981) Kinetics of Flow and Strain-hardening. Acta Metallurgica 29 (11): 1865–1875.
[164] Ambrosy F, Zanger F, Schulze V Jawahir IS (2014) An Experimental Study of Cryogenic Machining on Nanocrystalline Surface Layer Generation. *Procedia CIRP* 13: 169-174.
[165] Klocke F, Settineri L, Lung D, Priarone PC, Arft M (2013) High Performance Cutting of Gamma Titanium Aluminides: Influence of Lubricoolant Strategy on Tool Wear and Surface Integrity. *Wear* 302: 1136-1144.
[166] Fredj NB, Sidhom H (2006) Effects of the Cryogenic Cooling on the Fatigue Strength of the AISI 304 Stainless Steel Ground Components. *Cryogenics* 46: 439-448.
[167] Rotella G, Dillon Jr OW, Umbrello D, Settineri L, Jawahir IS (2014) The Effects of Cooling Conditions on Surface Integrity and Product Performance in Machining of Ti6Al4V Alloy. *International Journal of Advanced Manufacturing Technology* 71(1-4):47-55.
[168] Liu CR, Barash MM (1976) The Mechanical State of the Sublayer of a Surface Generated by Chip-removal Process—Part 1: Cutting with a Sharp Tool. *Journal of Manufacturing Science and Engineering* 98 (4): 1192–1199.
[169] Fredj NB, Sidhom H, Braham C (2006) Ground Surface Improvement of the Austenitic Stainless Steel AISI 304 Using Cryogenic Cooling. *Surface & Coatings Technology* 200: 4846-4860.
[170] Umbrello D, Pu Z, Caruso S, Outeiro JC, Jayal AD, Dillon Jr OW, Jawahir IS (2011) The Effects of Cryogenic Cooling on Surface Integrity in Hard Machining. *Procedia Engineering* 19: 371–376.
[171] Outeiro JC, Rossi F, Fromentin G, Poulachon G, Germain G, Batista AC (2013) Process Mechanics and Surface Integrity Induced by Dry and Cryogenic Machining of AZ31B-O Magnesium Alloy. *Procedia CIRP* 8:487-492.
[172] Zurecki Z, Ghosh R, Frey JH (2003a) Investigation of White Layers Formed in Conventional and Cryogenic Hard Turning of Steels. *ASME International Mechanical Engineering Congress and Exposition*: 211–220.
[173] Seah KHW, Rahman M, Yong KH (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.
[174] Leskovsek V, Kalin M, Vizintin J (2006) Influence of Deep-cryogenic Treatment on Wear Resistance of Vacuum Heat-treated HSS. *Vacuum* 80(6):507–518.
[175] Da Silva F, Franco SD, Machado AR, Ezugwu EO, Souza Jr AM (2006) Performance of cryogenically treated HSS tools. *Wear* 261(5–6):674–685.
[176] Sreerama Reddy TV, Sornakumar T, Venkatarama Reddy M, Venkatram R, Senthilkumar A (2009) Turning Studies of Deep Cryogenic-Treated P40 Tungsten Carbide Cutting Tool Inserts. *Machining Science and Technology* 13(2): 269-281.
[177] Ramji BR, Narasimha MHN, Krishna M, Raghu MJ (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.
[178] Firouzdor V, Nejati E, 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.
[179] Yong J, Ding C (2011) Effect of Cryogenic Treatment on WC–Co Cemented Carbides. *Materials Science and Engineering A* 528:1735–1739.
[180] Lal MD, Renganarayanan S, Kalanidhi A (2001) Cryogenic Treatment to Augment Wear Resistance of Tool and Die Steels. *Cryogenics* 41:149-155.
[181] Barron RF (1982) Cryogenic Treatment of Metals to Improve Wear Resistance. *Cryogenics* 22(8): 409-413.
[182] Vimal AJ, Bensely A, Lal DM, Srinivasan K (2008) Deep Cryogenic Treatment Improves Wear Resistance of En 31 Steel. *Materials and Manufacturing Processes* 23:369–376.
[183] Yang S (2012) Cryogenic Burnishing of Co-Cr-Mo Biomedical Alloy for Enhanced Surface Integrity and Improved Wear Performance. PhD Dissertation, Department of Mechanical Engineering, University of Kentucky.
[184] Zieliński A, Serbiński W, Majkowska B, Jażdżewska M, Skalski I (2009) Influence of Laser Remelting at Cryogenic Conditions on Corrosion Resistance of Non-ferrous Alloys. *Advanced in Materials Science* 9(4): 21-28.
[185] Singh H, Ubhi EBS, Lal EH (2013) Improvement in the Corrosion Rate and Mechanical Properties of Low Carbon Steel through Deep Cryogenic Treatment. *International Journal of Scientific and Technology Research* 2(6):10-29.
[186] Zhang W, Yang J, Dang J, Liu Y, Xu H (2013) Effects of Cryogenic Treatment on Mechanical Properties and Corrosion Resistance of LC4 Aluminum Alloy. *Advanced Materials Research* 627:694-697.
[187] Zhirafar S, Rezaeian A, Pugh M (2007) Effect of Cryogenic Treatment on the Mechanical Properties of 4340 Steel. *Journal of Materials Processing Technology* 186: 298–303.
[188] Baldissera P, Delprete C (2010) Deep Cryogenic Treatment of AISI 302 Stainless Steel: Part II – Fatigue and Corrosion. *Materials and Design* 31:4731–4737.
[189] Rotella G (2013) Sustainable Machining of Aerospace Alloys for Improved Product and Process Sustainability: Evaluation of Dry, Near-dry (MQL) and Cryogenic Machining Processes, PhD dissertation Politecnico di Torino.
[190] Jerold BD, Kumar MP (2012): Experimental Comparison of Carbon-dioxide and Liquid Nitrogen Cryogenic Coolants in Turning of AISI 1045 Steel. *Cryogenics* 52 (10): 569–574.
[191] Cordes S, Hubner F, Schaarschmidt T (2014) Next Genration High Performance Cutting by Use of Carbon Dioxide as Cryogenics. *Procedia CIRP* 14: 401-405.
[192] Huang, X., Zhang, X., Mou, H., Zhang, X. & Ding, H (2014) The influence of cryogenic cooling on milling stability. *Journal of Materials Processing Technology,* 214(12), pp.3169-3178.
[193] Zhao Z, Hong SY (1992a) Cooling Strategies for Cryogenic Machining from a Materials Viewpoint. *J. Materials Engineering and Performance* 1(5): 669-678.
[194] Zhao Z, Hong SY (1992b) Cryogenic Properties of Some Cutting Tool Materials. *Journal of Materials Engineering and Performance* 1(5): 705-714.

[195] Bhattacharyya D, Allen MN, Mander SJ (1993) Cryogenic Machining of Kevlar Composites. *Materials and Manufacturing Processes* 8(6): 631–651.
[196] Nalbant M, 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.
[197] Patil NG, Asem A, Pawade RS, Thakur DG, Brahmankar PK (2014) Comparative Study of High Speed Machining of Inconel 718 in Dry Condition and by using Compressed Cold Carbon Dioxide Gas as Coolant. *Procedia CIRP* 24: 86–91.
[198] Kramer A (2014) Gestaltungsmodell der kryogenen Prozesskühlung in der Zerspanung (In German), PhD, WZL RWTH Aachen.
[199] Putz, M.; Stoll, A.; Hösel, D.; Stolz, T.; Nitschke, S.; Noetzel, M. (2013) Entwicklung einer ressourceneffizienten Frästechnik mit kryogener Kühlung, Zwischenbericht SAB Teilprojekte Nr. 100102029, 100115338 und 100120135, P. 1 -13 (in German)
[200] Putz, M.; Stoll, A.; Hösel, D.; Stolz, T.; Nitschke, S.; Noetzel, M. (2014) Entwicklung einer ressourceneffizienten Frästechnik mit kryogener Kühlung, Sachbericht SAB Teilprojekte Nr. 100102029, 100115338 und 100120135, P. 1 -84 (in German)
[201] Dionne J, Schiller D, Jackson DP (2012) Method and Apparatus for Thermal Control Within a Machining Process, Cool Clean Technologies, US Patent, US 2012/0237311 A1.
[202] Sun Y, Huang B, Puleo DA, Jawahir IS (2015) Enhanced Machinability of Ti-5553 Alloy from Cryogenic Machining: Comparison with MQL and Flood-cooled Machining and Modeling. *Procedia CIRP* 31: 477-482.
[203] Richter A (2015) Cryogenic Machining Systems can Extend Tool Life and Reduce Cycle Times. *Cutting Tool Engineering* 67 (2): 50–57.
[204] Horn W (2011) Zerspanung mit innerer Stickstoffkühlung. Fachkolloqium: Innovative Zerspanwerkzeuge und Bearbeitungskonzepte, Dresden.
[205] Venugopal K, Tawade R, Prashanth P, Paul S, Chattopadhyay AB (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* 217:1697–1707.
[206] Aurich JC, Herzenstiel P, Sudermann H, Magg T (2008) High-performance Dry Grinding Using a Grinding Wheel with a Defined Grain Pattern. *Annals of the CIRP - Manufacturing Technologies* 57(1): 357-362.
[207] Klocke F, Bücker C, (1996) Trockenschleifen-Grenzbetrachtung zur Kühlschmierstoffreduzierung. Industriediamantenrundschau, 30(1): 26-35.
[208] Brinksmeier E, Heinzel C, Wittmann M (1999) Friction, Cooling and Lubrication in Grinding. *Annals of the CIRP - Manufacturing Technologies* 48(2): 581-598.
[209] Brinksmeier E, Walte, A, Brockhoff T (1997) Minimum Quantity Lubrication in Grinding. *2nd International Machining and Grinding Conference*, Dearborn, Michigan, USA, Sept. 8-11, SME-Paper MR97-230.
[210] Inasaki I, Tönshoff HK, Howes TD (1993) Abrasive Machining in the Future. *CIRP Annals – Manufacturing Technologies* 42(2): 723-732.
[211] Manimaran G, Pradeep KM, Venkatasamy R (2014) Influence of Cryogenic Cooling on Surface Grinding of Stainless Steel 316. *Cryogenic*, 59: 76-83.
[212] Murthy JKN, Chattopadhyay AB, Chakrabarti AK (2000) Studies on the Grindability of Some Alloy Steels. *Journal of Materials Processing Technology* 104: 59-66.
[213] Hoffmeister H-W, Maiz K (2007) Flachschleifen metallischer Werkstoffe unter Verwendung von flüssigem Stickstoff zur Kühlung. In: Jahrbuch Schleifen, Honen, Läppen und Polieren, Editors: H.-W. Hoffmeister, B. Denkena, Vulkan-Verlag, Essen,
[214] Maiz K, (2009) Flachschleifen metallischer Werkstoffe unter Verwendung von flüssigem Stickstoff zur Kühlung. Dr.-Ing. Dissertation, TU Braunschweig, Essen, Germany.
[215] Reddy P, Gosh A (2014) Effect of Cryogenic Cooling on Spindle Power and G-ratio in Grinding of Hardened Bearing Steel. *Procedia Materials Science* 5: 2622-2628.
[216] Nguyen T., Zarudi I, Zhang LC (2007) Grinding-hardening with Liquid Nitrogen: Mechanisms and Technology. *International Journal of Machine Tools & Manufacture* 47: 97-106.
[217] Brinksmeier E, Brockhoff T, (1996) Utilization of Grinding Heat as a New Heat Treatment Process. *Annals of the CIRP - Manufacturing Technologies* 45(1): 283-286.
[218] Nguyen T, Zhang LC (2010) Grinding–hardening using Dry Air and Liquid Nitrogen: Prediction and Verification of Temperature Fields and Hardened Layer Thickness. *International Journal of Machine Tools & Manufacture* 50: 901-910.
[219] Lee P-H, Lee SW, (2010) Experimental Characterization of Meso-scale Grinding Processusing Compressed Chilly Air. *Trans NAMRI/SME* 38: 185-90.
[220] Oliveira JFG, Silva EJ, Coelho RT, Brozek L, Bottene AC, Marcos GP (2015) Dry Grinding Process with Workpiece Precooling. *CIRP Annals – Manufacturing Technologies* 64(1): 329-332.
[221] Karpuschewski B, Emmer T, Schmidt T, Petzel M (2013) Cryogenic wet-ice blasting-Process Conditions and Possibilities. *CIRP Annals – Manufacturing Technologies*, 62(1): 319-322.
[222] Linke B, Moreno J (2015) New Concepts for Bio-inspired Sustainable Grinding. *Journal of Manufacturing Processes* 19: 73-80.
[223] Durham T.F., McClintock, R.M., Reed, R.P. (1962), Cryogenic Materials Data Handbook (PB 171809) Cryogenic Engineering Laboratory, Office of Technical Services, US Department of Commerce
[224] Hurlich A. (1963), Low Temperature Metals, Chemical Engineering, 70/24, pp 104-112
[225] Hickey C.F. (1962) Mechanical properties of Titanium and Aluminium alloys at cryogenic temperatures, Technical report WAL TR 2340.2/I Watertown Arsenal Laboratories, Watertown, Massachusetts.
63: 119-134.
[226] Kaufman J. G., Wanderer E. T. (1973) The tensile properties of Aluminum alloys formed at cryogenic temperatures, Advances in Cryogenic Engineering Vol. 18, pp 170-174.
[227] Schneider R., Heine B., Grant R.J. (2014), Mechanical behaviour of commercial Aluminium wrought alloys at low temperatures, Light Metal Alloys Applications, Imtech
[228] Park D.H., Choi S.W., Kima J.H., Lee J.M. (2015) Cryogenic mechanical behavior of 5000- and 6000-series aluminum alloys: Issues on application to offshore plants, Cryogenics Vol. 68, pp 44–58.
[229] Park W.S., Chun M.S., Han M.S., Kim M.H., Lee J.M. (2011) Comparative study on mechanical behavior of low temperature application materials for ships and offshore structures: Part I-Experimental investigations, Materials Science and Engineering: A, Vol. 528/18, pp 5790–5803.
[230] van den Beukel A. (1975) Theory of the effect of dynamic strain aging on mechanical properties. Physica Status Solidi (a) 30 (1): 197-206.
[231] Lebyodkin M., Brechet Y., Estrin Y., Kubin L. (1996) Statistical behaviour and strain localization patterns in the Portevin-Le Chatelier effect. Acta Materialia 44 (11): 4531-4541.
[232] Hendrickx G. (2015) Parameter study of Incremental Forming in cryogenic environment, Dissertation KU Leuven.
[233] Matsui K., Sugita T., Ichimoto T. (1998) Lubricant composition for cryogenic forming of aluminium or aluminium alloy sheets. US Patent 5, 761, 941.
[234] Lord D. E., Meisner L. F. (1976) A cryoforming evaluation using high purity nickel, Lawrence Livermore Laboratory.
[235] Imgram, A.G. (1965) Cryogenic forming of type 301 stainless steel, Battelle Memorial Institute, Columbus OH.
[236] Daigle, D.L. (1965) Evaluation of three Arde-Portland cryogenic stretched formed subscale rocket motor cases, Thiokol Chemical Corp. Huntsville AL
[237] Selines R. J., Van den Sype J. S. (1979) Cryogenic forming. US Patent 4159217A
[238] Selines R.J. (1981) Method for deep drawing,, US Patent 4290293A
[239] Vanhove H, Mohammadi A, Duflou JR (2016) Incremental Forming of Aluminium Alloys in Cryogenic Environment, Proceedings of ESAFORM 2016 Conference.
[240] Arrazola PJ, Özel T, Umbrello D, Davies M, Jawahir IS (2013) Recent Advances in Modelling of Metal Machining Processes. *CIRP Annals – Manufacturing Technology* 62(2): 695–718.
[241] Childs THC, Maekawa K, Maulik P (1988) Effects of Coolant on Temperature Distribution in Metal Machining. *Materials Science and Technology* 4:1006–1019.
[242] Deb S, Yao SC (1989) Analysis on Film Boiling Heat Transfer of Impacting Sprays. *International Journal of Heat and Mass Transfer* 116:167–172.
[243] Zheng Y, Li H, Olson WW, Sutherland JW (2000) Evaluating Cutting Fluid Effects on Cylinder Boring Surface Errors by Inverse Heat Transfer and Finite Element Methods. *Journal of Manufacturing Science and Engineering* 122: 377–383.
[244] Sozbir N, Chang, YW, Yao SC (2003) Heat Transfer Impacting Water Mist on High Temperature Metal Surfaces. *Trans of ASME-Journal of Heat Transfer* 125: 70–74.
[245] Ding Y, Hong SY (1995) A Study of Cutting Temperatures in Machining Processes Cooled by Liquid Nitrogen. *Technical Paper of the North American Manufacturing Research Institution of SME*: 115–119.
[246] Kheireddine AH, Ammouri AH, Lu T, Dillon OW, Hamade RF, Jawahir IS (2015) An Experimental and Numerical Study of the Effect of Cryogenic Cooling on the Surface Integrity of Drilled Holes in AZ31B Mg Alloy. *International Journal of Advanced Manufacturing Technology* 78, 269-279.
[247] Outeiro JC, Umbrello D, M'Saoubi R, Jawahir IS (2015) Evaluation of Numerical Models for Predicting Surface Integrity in Metal Machining. *Machining Science and Technology* 19(2): 183-216.
[248] Bordin A, Imbrogno S, Rotella G, Bruschi S., Ghiotti A, Umbrello D (2015) Finite Element Simulation of Semi-finishing Turning of Electron Beam Melted Ti6Al4V under Dry and Cryogenic Cooling. *Procedia CIRP* 31: 551-556.
[249] Mishima K, Kakinuma Y, 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.
[250] Kakinuma Y, Yasuda N, Aoyama T (2008) Micromachining of Soft Polymer Material applying Cryogenic Cooling. *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 2(4): 560-569.
[251] Kakinuma Y, Kidani S, Aoyama T (2012) Ultra-precision Cryogenic Machining of Viscoelastic Polymers. *CIRP Annals - Manufacturing Technology* 61(1): 79-82.
[252] Dhokia VG, Newman ST, Crabtree P, Ansell MP (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.
[253] Pusavec F, Krajnik P, Kopac J (2010) Transitioning to Sustainable Production–Part I: Application on Machining Technologies. *Journal of Cleaner Production* 18:174–184.