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Cryogenic Machining through the Spindle and Tool for Improved Machining Process Performance and Sustainability: Pt. I, System Design

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Abstract

Cryogenic machining is considered a sustainable alternative to machining with flood cooling. This paper describes a sustainable cryogenic machining solution which considers not only the conventional machining performance, but also the overall sustainability performance in each of the sustainability elements: economy, environment and society. A brief review of the potential benefits and drawbacks of cryogenic machining is presented in this paper. Using factors as a guideline, an optimized cryogenic cooling system and tooling has been developed. The cooling system is optimized for flow quality, thermal insulation, controllability and safety. The innovative cryogenic cutting tool design utilizes built-in coolant channels to achieve the optimal process performance. This solution incorporates outstanding cooling capability for optimal performance, while minimizing or eliminating the adverse effects.

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Keywords: Cryogenic machining; Machining coolant; Sustainable machining; Cutting tool; Cryogenic cooling; Operator friendly;

1. Introduction

Cryogenic machining, which uses liquid nitrogen as the cooling media, is considered a sustainable alternative to conventional flood cooling application used in the machining process. Through years of research, work of cryogenic machining has gradually accumulated in the aspects of the performance, mechanism and application benefits. This

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leads to a good fundamental understanding of cryogenic machining's mechanism. In this paper, the focus is placed on implementing cryogenic machining as a practical application. The benefits and counter measures for the potential limitations of the technology, concerns and critical design features in implementing cryogenic machining are presented.

2. Background and Previous Work

2.1. Sustainable cooling solutions for a machining process

The machining process is an important part of the manufacturing process thus it is expected to have a huge impact by improving the sustainability performance [1]. Among the elements of machining, the conventional coolant application has been considered a critical limiting factor to achieve better sustainability performance. Typical alternative approaches to conventional flood cooling are dry machining, minimum quantity lubrication (MQL) and cryogenic machining. An overview of the effectiveness and application of the typical cooling and lubricating strategies are presented by Jawahir et al. [2], as shown in Table 1 below.

Table 1: Effectiveness and application of various cooling and lubricating strategies [2]

Effect of the cooling and lubricant strategy	Flood (emulsion/oil)	Dry (compressed air)	MQL (oil)	Cryogenic (LN2)	Hybrid (LN2 + MQL)
Cooling	Good	Poor	Marginal	Excellent	Excellent
Lubrication	Excellent	Poor	Excellent	Marginal	Excellent
Chip Removal	Good	Good	Marginal	Good	Good
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

2.2. Heat transfer mechanism in cryogenic machining

The idea of cryogenic machining relies on the superior cooling capability of liquid nitrogen. To quantify the heat transfer on the coolant contact surface, the following equation is typically applied:

$$q = h \cdot \Delta T = h \cdot \left(T_{surface} - T_{coolant}\right) \tag{1}$$

where, q is the heat flux on the surface, in W/m^2; h is the surface heat transfer coefficient, in W/(m^{2}ºC); ΔT is the temperature difference between the solid surface temperature, $T_{surface}$, and the coolant media temperature, $T_{coolant}$, respectively, in ºC.

The low coolant temperature of liquid nitrogen, -196ºC under atmospheric pressure, yields a larger temperature difference and hence provides great cooling potential. Equally important is that the cooling mechanism is different with liquid nitrogen compared to other coolant choices. When saturated liquid nitrogen contacts the solid surface, the dominant heat transfer mechanism is forced convective boiling instead of just forced convection as in most other coolant scenarios. The different heat transfer mechanism gives a dramatically different value in surface heat transfer coefficient, especially when forced convection conditions are applied [3]. Both the larger temperature difference and the high value of surface heat transfer coefficient contribute to the high value of heat flux.

To maintain the high heat flux during the boiling heat transfer, an important factor is the phase ratio of the flow. Being in saturated state most of the time during storage, transportation and delivery, liquid nitrogen flow delivered to the target surface could contain a certain portion of gas phase. This could reduce the liquid wetting and thus suppress the boiling heat transfer. A sufficient flow rate and thermal insulation throughout the delivery line helps to solve the problem [3].

Thermal equilibrium state is not always achieved during normal machining with any of the afore-mentioned cooling solutions. Especially in cyclic-loaded or interrupted cutting processes, the stable condition is a dynamic cyclic status. It is complicated to assess the thermal behavior in such a scenario. The corresponding transient thermal analysis is still based on Equation 1, which serves as one of the boundary conditions. Detailed analysis is required for a comprehensive study.

3. Design for Sustainable Cryogenic Machining

3.1. Key features in sustainable cryogenic machining system design

Considering the various aspects mentioned in Section 2, it is critical to have a systematic approach addressing the appropriate tooling, delivery and system integration designs in cryogenic machining. Some key points are summarized here.

Instead of solid phase contact and gas phase convective heat transfer, the critical thermal advantages of choosing liquid nitrogen as the cooling media are liquid phase surface wetting and forced convective boiling heat transfer. Efficient liquid nitrogen cooling needs to incorporate a liquid nitrogen stream with high liquid phase ratio and sufficient flow velocity, which would flush away generated nitrogen gas to minimize the Leidenfrost effect [4].A low thermal resistance in the thermal path at the point of cut and sufficient contact time near the cutting zone are also important.

To avoid excessive workpiece and machine tool cooling, flow path of the liquid nitrogen delivery should be thermally insulated, and the flow rate of liquid nitrogen and its coverage area should be carefully controlled. On the other side, controlled cooling on machined surface could improve the surface integrity [2] and reduce thermal expansion error.

Since the cryogenic cooling medium evaporates and leaves no residue, there is no cleaning process required. Minimum contamination requirements on certain products could be met without extra investment. Disposal of the used cooling medium is not required for cryogenic machining, while the conventional coolant needs regulated post-use treatment. Nitrogen is not a greenhouse gas (GHG) and is naturally a major part of the atmosphere, thus its application has little environment influence other than the energy consumed in liquefaction and transportation. All these further improve the sustainability performance of the process and the manufactured product.

Lack of a cooling-performance oriented, industrial and user friendly cryogen delivery system has slowed, if not prevented, wide spread realization of benefits resulting from cryogenic machining and associated sustainability gains. Research on cryogenic machining and its benefits were well documented through work mainly performed in research laboratories using delivery methods appropriate only in laboratory settings [2]. Though the benefits in various aspects through the application of cryogenic machining have been addressed in this work, it is believed that a sustainability oriented cryogenic coolant delivery system design and corresponding cutting tool optimization under cryogenic conditions are critical to fulfill these potential benefits in the production environment.

3.2. System overview

Recently 5ME LLC has introduced a commercialized, industrial robust and user friendly cryogenic kit for through spindle and through tool delivery of liquid nitrogen to cool the cutting edges. It can be applied as an add-on to installed machine tools or as a built-in option on new ones. It provides cooling at the cutting zone by carrying liquid nitrogen through the spindle and through the tool via thermally insulated fluid passages. The exhaust flow can be controlled with different cutting tool designs. The direct exposure of cryogenic fluid to the work piece and machine tool is under control with such a structure, unlike the externally sprayed cryogenic cooling method.

Cryogenic cooling of a tool's cutting edge is achieved through internal channels in the tool. Extremely low temperature of the cryogenic fluid at its saturated condition combined with forced convective boiling heat transfer effectively cools the cutting edge. This results in low tool wear and enables higher cutting speeds during workpiece machining compared to conventional coolant.

The flow rate of the liquid nitrogen is controlled so that the overall flow rate is not excessive and flow exiting the exhaust holes on the cutting tool contain very little liquid nitrogen. The gas phase of nitrogen has a very limited cooling capability so the thermal stability of the workpiece and machine tool would not be altered. Although nitrogen gas is naturally the dominant part of the atmosphere, a portable oxygen monitor is recommended as a safety measure against asphyxiation. The potential mechanism of asphyxiation for liquid nitrogen based cryogenic machining is the displacement of oxygen and is unlikely to occur with a low flow rate, especially considering that nitrogen gas density is less than air so it tends to rise and not concentrate in enclosed areas. Also, as the system utilizes a low pressure and low flow rate liquid nitrogen based design, it does not carry typical safety hazards associated with high pressures. Skin penetration is not likely to occur with such a low-pressure system.

3.3. Delivery and control system

The implementation details of a through the spindle and through the tool delivery system of liquid nitrogen are described in Figure 1 below.

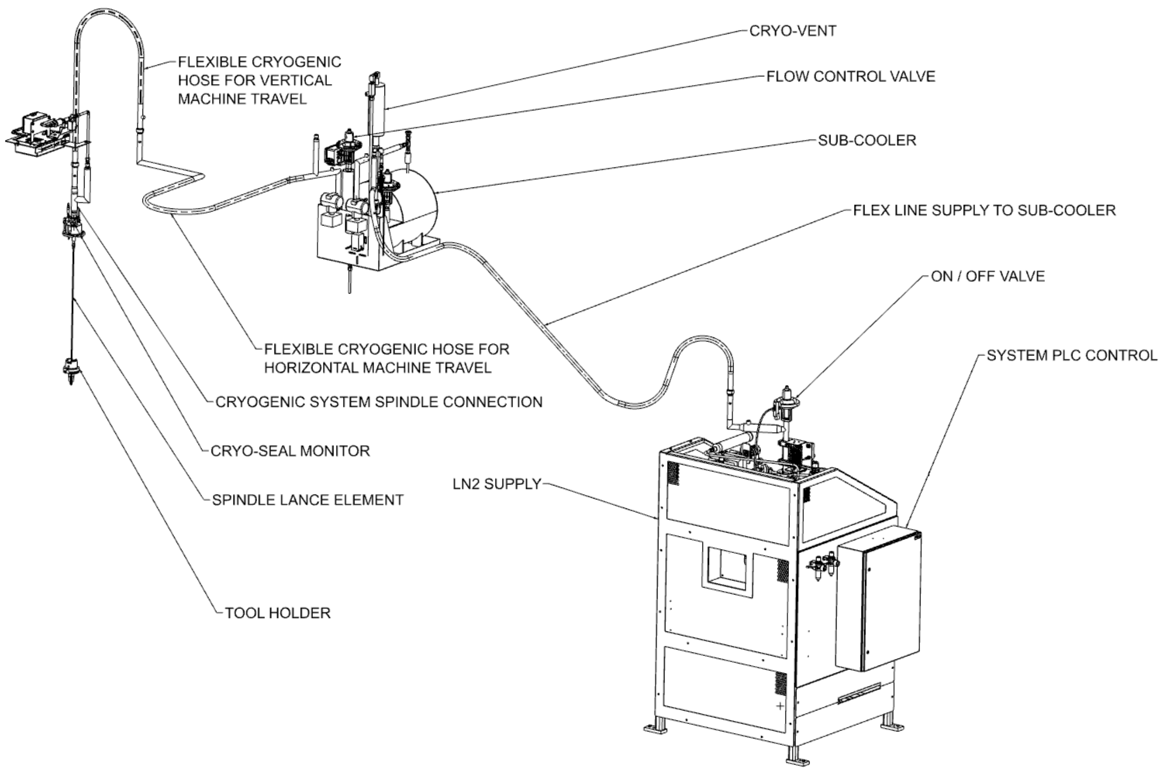


Figure 1: System overview

The functions of the various components identified in Figure 1 are as follows. A rechargeable cryogenic dewar appropriately sized for user requirements stores liquid nitrogen at predetermined pressure and acts as the source of cryogen. The dewar is equipped with means for pressure building and relieving to maintain the source pressure requirements. The source dewar is also equipped with devices such as a cryogen quantity monitor (weight or level), a primary pressure safety relief valve and secondary pressure safety rupture disc, and remotely controlled main flow on/off valve and fill valve.

The cryogen stored in the dewar is at saturated fluid condition. The saturated liquid is drawn from bottom of dewar and as it travels to the tool picks up heat and drops in pressure. Both the heat input and the pressure drop along the flow path changes the quality of fluid reaching the tool. Here, fluid quality is defined in terms of percent or fraction of mass of liquid in the fluid. On its way to the tool the cryogen is subcooled in the sub-cooler so that the fluid delivered to the tool is of high quality, in other words high liquid phase content.

The fluid conduits are made of industry standard flexible cryogenic hoses. They are constructed using inner and outer concentric stainless steel bellows tubing and contain multilayer thermal insulation and vacuum in the annular space. Multilayer thermal insulation and vacuum help in minimizing the radiative and convective heat leak from ambient into cryogenic fluid. Loops made of bellows tubing can effectively handle translational motion in a single plane but do not tolerate twisting. Therefore, several individual loops made of bellows tubing provide the needed flexibility to accommodate the various translational movements of the machine tool spindle along different axis.

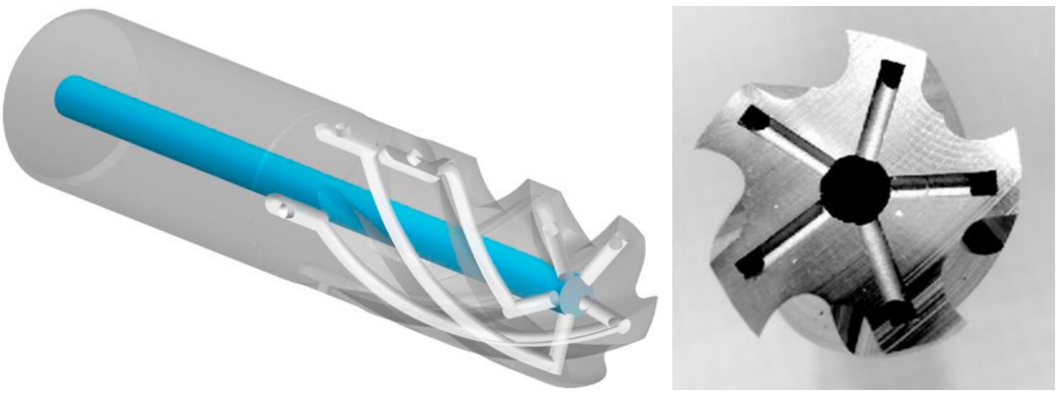
Part of the fluid path through the machine tool spindle, referred here as a lance, is constructed using inner and outer concentric stainless steel tubing and the annular space between the outer and inner tubing is under vacuum. Thermal stresses due to thermal contraction in the lance are minimized by incorporating a short bellows section. The lance rotates with the tool spindle. On one end of the lance, the connection between the lance and tool holder is achieved by employing static cryogenic radial seals. On the other end of the lance, the transition / connection between rotary and non-rotary components is achieved by employing dynamic cryogenic radial rotary seals. The dynamic seal is actively monitored for its sealing condition and the user is alerted by the controller interface if a failure is detected.

A cryogenic control valve is used to set the required flow rate. The cryogenic kit system operation is monitored with various sensors and controlled by a dedicated programmable logic controller (PLC). There are two modes of operation, namely, manual mode and CNC mode. The main difference is that in the CNC mode the PLC receives the required flow rate information from the CNC's controller whereas this information is provided by the operator in manual mode. This enables the flexibility of different workstation organization and seamless machine tool integration.

3.4. Cryogenic cutting tools

Tool holders used in the cryogenic machining system under discussion are backward compatible with standard cutting tool holders and tooling systems. They can be used as conventional holders without any changes. Internally the thermal function of the holder is improved by adding insulation and sealing structures that are designed for cryogenic conditions. This minimizes the thermal interactions between the cryogenic coolant and the machine tool. The insulation material and sealing structure is particularly critical for the flow quality and the thermal stability of the spindle front section.

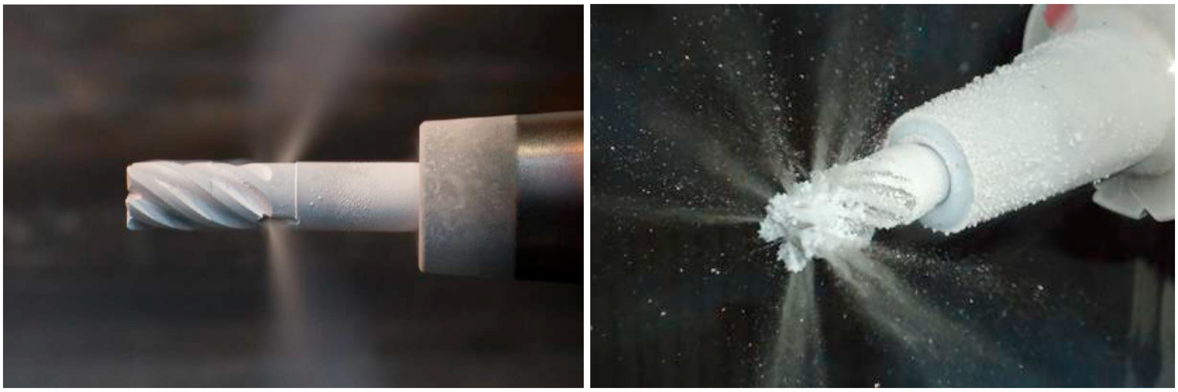
The cutting tools have through the tool liquid nitrogen channels built in [5] as shown in Figure 2. The channels are designed taking into consideration the liquid nitrogen flow condition, the thermal resistance between the cutting edge and the liquid channel, and the mechanical structural strength of the flute.



(a) (b)

Figure 2: Internal structure of a 5ME BlueZone™ milling cutter: (a) internal structure schematic; (b) a cross section cut-off in the front [5]

The exhaust holes can be placed at different locations to accommodate different purposes. For example, the exhaust holes can guide the cryogenic exhaust flow away from the workpiece to prevent dimensional change due to excessive cooling. The exhaust holes can also guide the cryogenic exhaust flow to spray onto the machined surface to reduce local thermal expansion and improve surface integrity of the part. Figure 3 shows a sample for each of the two types, respectively.



(a) (b)

Figure 3: 5ME BlueZone™ milling cutters in use: a) back venting design; b) flute/front venting design

In developing tooling for cryogenic machining, a good part of the conventional tooling development experience can be applied. However, differences in the temperature distribution, cutting mechanics, tribological behavior and material characteristics in comparison to conventional cooling scenarios, must be given due consideration.

3.5. Summary: system design elements

Table 2 and Table 3 summarize the potential benefits and drawbacks of cryogenic machining according to the general understanding of cryogenic machining as mentioned in literatures [2-4], and proposed ways to accommodate the benefits and mitigate drawbacks.

Table 2: System design elements for maximizing cryogenic machining benefits

Potential Benefits	Critical Mechanism	Design Features to Accommodate
Great cooling capability	Boiling heat transfer; Leidenfrost effect	Ensure high liquid phase ratio, sufficient flow rate, minimize thermal resistance, maximize heat dissipation
Good product quality	Surface integrity, distortion control	Controlled workpiece cooling with optimized flow venting and flow rate control
Low power requirements	Self-driven by vaporized nitrogen	Low pressure, low flow rate system, vaporizer and pressure maintenance system
Low maintenance	Non-corrosive, inert and evaporative coolant	Closed delivery line, delivery line purge before system shut-down
Eliminate contact dermatitis	Non-hazardous chemical, no splashing	Flow rate control to eliminate splashing, making use of the evaporative coolant
Reduce carbon foot-print	Low pressure, low flow rate	Optimized coolant usage
No safety risk of slippery surfaces	Low flow rate, evaporative coolant	Low flow rate of evaporative coolant eliminates accumulation on the ground

Table 3: System design elements for eliminating potential cryogenic machining drawbacks

Potential Drawbacks	Critical Mechanism	Design Features to Accommodate
(Lack of) Lubrication	LN lubrication effect	Optional MQL assistance
(Lack of) Chip evacuation	Flow flushing	Optional compressed air assistance
Localized workpiece cooling	Boiling and convective heat transfer	Guided exhaust flow direction: cooling workpiece for surface integrity
Localized machine tool cooling	Conductive heat transfer	Well-designed thermal insulation
Global workpiece and machine tool cooling	Convective heat transfer	Guided flow to avoid excessive liquid coverage, controlled flow rate, machine venting
Excessive coolant consumption	Flow rate control	Enclosed flow contact, easy exhaust control and even closed loop potential
Asphyxiation hazard	Displacement of oxygen	Portable oxygen monitor
Operator frostbite hazard	Low temperature exposure	Only the cutting tool is at low temperature, handle with insulated gloves if operated manually; otherwise no special care needed

4. Summary

A brief review on the background of cryogenic machining is presented. It reveals the potential benefits and critical design considerations of the technology, especially in sustainability aspects. The fundamental mechanism of cryogenic machining is also reviewed to emphasize the scientific basis for its engineering implementation.

Based on the background in the review, the critical design targets and constraints are outlined. Then the system components are reviewed and along with illustrations about the design features. The system comes in two major distinguishable sub-systems, the liquid nitrogen delivery system and the cutting tool system. The prior part focuses on flow control for a stable, single phase liquid nitrogen stream. The later part is based on the heat dissipation mechanism in machining, which focuses on encouraging efficient boiling heat transfer around the cutting zone. The designs are carefully evaluated for cost-efficiency, resource efficiency, environmental-friendliness and operator safety and health.

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