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Analysis of the influence of nitrogen phase and surface heat transfer coefficient on cryogenic machining performance

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ABSTRACT

This paper presents the influence of the nitrogen fluid phase on the surface heat transfer coefficient in cryogenic machining. A novel optical nitrogen phase sensor was developed for characterizing the cryogenic fluid phase. Surface heat transfer coefficients were established experimentally by using a new heat transfer model for cryogenic machining. A finite element model was developed utilizing experimental data for Inconel 718. Using it, the process behavior with varying nitrogen phases was simulated. Determining the minimal, but sufficient amount of coolant flow-rate, in combination with the desired fluid phase at the delivery, was found to be the key for achieving truly sustainable cryogenic machining.

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1. Introduction

Sustainable manufacturing trends dictate the need for developing cleaner processes that are environmentally benign and have no adverse health effects. (Shokrani et al., 2012) have emphasized that the recognition of ecological problems of using conventional cooling lubrication fluids in machining processes and developing governmental regulations have resulted in increasing machining costs and searching for alternatives. One of the emerging sustainable manufacturing process alternatives is cryogenic machining that utilizes fluids at extremely low temperatures in the machining process. Cryogenic machining and nitrogen coolant are the common terms used to describe the process. An extensive and recent review on this topic has been published by Yildiz and Nalbant (2008). As can be seen from the review, cryogenic machining can beneficially contribute to machining performances. For example, by using cryogenic machining, Bermingham et al. (2011) show improvement in cutting forces, tool-life and chip morphology. In Dhar and Kamruzzaman (2007), an analysis of cryogenic machining's positive influence on temperatures and machined surface's characteristics is also included. However, from machining performance point of view, a lot of contradictory results can be seen (increase of cutting forces, premature fracture of the cutting inserts, etc.). One of the very important characteristics of nitrogen is its phase that can significantly change the actual cryogenic condition. In fact, liquid nitrogen (LN), due to its extremely low temperatures and its low saturation (−196 °C at atmospheric pressure of 10^5 Pa), has a high tendency for evaporation. Thus, the phase at the delivery may vary (either gas or liquid) and with it the outer boundary conditions of the machining process (Fig. 1). The physical properties of N_2 fluid, such as density (ρ), specific heat (c_p), viscosity (μ), thermal conductivity (λ), reported in Weisend (1998), directly depend on its phase (Fig. 2):

- N_2 liquid (−196 °C): $\rho = 803.6\ \mathrm{kg/m^3}$, $c_p = 2.046\ \mathrm{kJ/kg\,K}$, $\mu = 1.463 \times 10^{-4}\ \mathrm{Pa\,s}$, $\lambda = 1.320 \cdot 10^{-1}\ \mathrm{W/m\,K}$.
- N_2 gas (−196 °C): $\rho = 4.979\ \mathrm{kg/m^3}$, $c_p = 1.351\ \mathrm{kJ/kg\,K}$, $\mu = 0.05331 \times 10^{-4}\ \mathrm{Pa\,s}$, $\lambda = 0.07658 \times 10^{-1}\ \mathrm{W/m\,K}$.

The liquid phase is characterized by a higher specific heat, viscosity and thermal conductivity. This practically means that:

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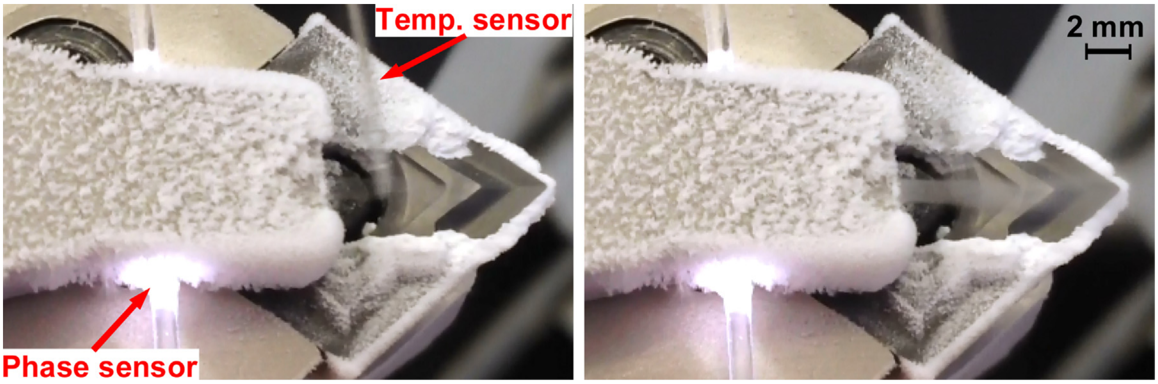

Fig. 1. Comparison of gas (left) and liquid nitrogen (right) flow stream from the nozzle, both at −196 °C.

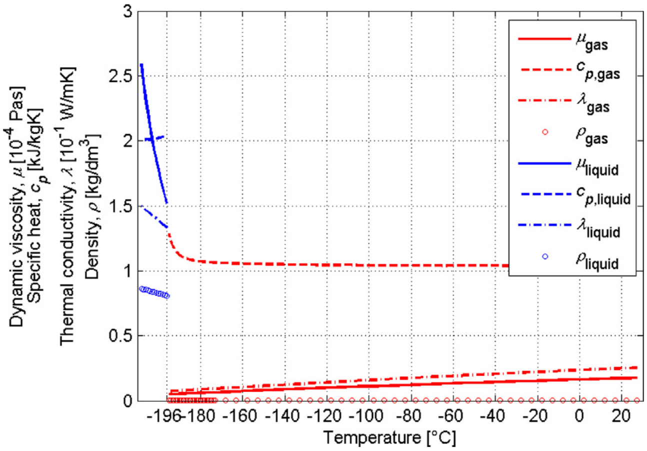

Fig. 2. Nitrogen properties along the 10^5 Pa isobar (gas vs. liquid phase).

- a larger amount of energy is required to raise the temperature of a given mass of liquid by 1 °C compared to the same mass of gas;
- some of the small end volumes would not be reachable in the liquid phase due to significantly higher viscosity (by a factor of 30), and the cooling and lubrication properties will differ from those of the gas phase;
- the thermal conductivity, comparing gaseous and liquid phases, differs by a factor of larger than 10. This means that in the case of the liquid nitrogen phase, the heat transfer across the liquid occurs at a higher rate and does not depend on the work material that is machined.

When correlating these comparisons with the cooling capacity/capability of different nitrogen phases, it has to be taken into account that when nitrogen is delivered to the cutting zone in the liquid phase, a larger amount of heat is used due to its more favorable physical properties. Additionally, with the boiling mechanism (latent heat of vaporization for nitrogen is $Q_L = 199$ kJ/kg), a much higher cooling capability is expected with the liquid phase delivery.

Reviewing the state-of-the-art: (i) environmental cutting fluids and techniques (Debnath et al., 2014), (ii) cooling techniques for improving productivity (Sharma et al., 2009), and (iii) extensive review on cryogenic machining (Yildiz and Nalbant, 2008), it is quite evident that there is no knowledge or information on the actual phase of the delivered medium in cryogenic machining and, to the knowledge of the authors, this was not considered being important in any previous work. However, in cryogenic machining, the workpiece surface temperatures are normally higher than the saturation point of nitrogen and this means that the boiling heat transfer occurs when liquid phase is delivered to the machining zone. Heat transfer is therefore affected and becomes temperature-dependent. The heat exchange coefficient used for modeling this effect cannot be considered as constant anymore, but rather as a function of the temperature. This has a significant effect on the machining process performance and the robustness of the machining process.

There is actually only a very small amount of published works about the heat transfer mechanism in cryogenic machining. This is especially fundamental as far as FE modeling of cryogenic machining is concerned, as the surface heat transfer coefficient (h) is an important input to the machining process model. Most published works utilize the constant referenced values. The most quoted among these is the work by Ding and Hong (1995). The values found in the published literature differ among references. In Hong and Ding (2001a), $h_{LN} = 23{,}270–46{,}750$ W/m^2 °C, in Hong and Ding (2001b), $h_{LN} = 48{,}270–74{,}950$ W/m^2 °C, in Jin et al. (2009), $h_{LN} = 0–3500$ W/m^2 °C, in Kheireddine et al. (2015) and Rotella and Umbrello (2014), h is presented as a constant $h_{LN} = 20{,}000$ W/m^2 °C, and in Dix et al. (2014), $h_{LN} = 23{,}300–46{,}800$ W/m^2 °C and $h_{gasN} = 30$ W/m^2 °C. It can be summarized that there is a large variation in h values, and almost no difference can be seen in the above-mentioned works between liquid and gas phases. In the majority of the published works, uniform values are still used without considering a potential dependency on the surface overheat temperature (relative temperature difference between surface and cooling fluid). There exist, however, just a few published papers where the temperatures and phase dependency are mentioned. In the majority of these cases, the values used for h are not measured, but are referenced from prior works. When tracking back the references, in most cases, the original source reference is the previously mentioned work by Ding and Hong (1995). This draws a greater interest in this field as there is a lack of fundamental understanding of the heat transfer mechanism and measurement of surface heat transfer coefficients (h) in cryogenic coolant applications in machining processes. Also, it raises the importance of the delivered phase in the machining process performance.

The need for assuring a stable machining process inevitably requires the control of the cryogenic fluid phase at the outlet of the delivery nozzle, which thus enables the prevention of thermal shocks. The first step in this direction is to sense and accurately quantify the phase of nitrogen in the nozzle. Unfortunately, current cryogenic machining technologies, which cover different directions and orientations of nitrogen delivery to the machining zone area, do not analyze or even mention problems/benefits related to possible variations in the cryogenic fluid phase. Additionally, there is currently no compact device that can monitor and sense the nitrogen fluid phase status within the delivery nozzle. Furthermore, there is no liquid nitrogen machining system on the market that would be capable of sensing the phase or would offer the possibility of robust

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