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Modeling of drilling assisted by cryogenic cooling for higher efficiency

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ABSTRACT

The energy consumption of machining operations is significantly influenced by the cooling strategy. In cases of high-performance drilling, high thermal stress on the tool makes adequate cooling necessary. Only cryogenic machining provides the option of lubricant-free processing, resulting in low tool wear, even at high removal rates, due to significant reductions in tool temperatures. Compared to actual tests, verified finite-element process models showed that suitable tool geometry, especially in terms of the positions of the cooling channels, is fundamental for efficient cryogenic drilling. The process model developed is based on a new combination of different approaches for modeling a cryogenically cooled tool.

1. Cryogenic machining

The minimization and avoidance of cooling lubricants is a general goal for improving the efficiency of machining processes. However, the mechanical and thermal stability of the cutting materials are limited as to be able to machine without cooling in problematic processes such as drilling. Here it is important to cool the highly thermally stressed cutting edges efficiently and as far as possible without residues. Cryogenic cooling, which uses extremely cold liquefied gases, may well be a promising approach for this.

1.1. State of the art

Comparative studies of turning TiAlNB45-2-2 with liquid nitrogen (LN2) showed a significant reduction in tool wear compared to conventional wet machining, minimum-quantity lubrication and high-pressure cooling with emulsion [1].

In addition to a reduction in wear, significantly better geometric and material-specific surface properties were produced [2] and a reduction in burr formation could be achieved [3].

There are different methods of using cryogenic cooling during machining. Thus, in addition to the coolant type – LN2 and carbon dioxide – there are differences with respect to the coolant supply system, as shown in Table 1 [4].

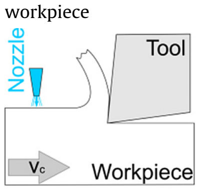
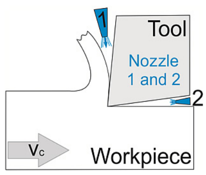
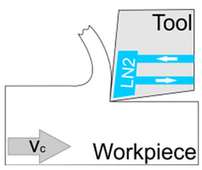
1.2. Modeling of cryogenic cooling in machining processes

Various approaches to modeling cryogenic cooling can be found in literature. Thus Kheireddine et al. [5] modeled cryogenic cooling when drilling using universal boundary conditions to calculate the convective heat flow q:

$$q = h_c(T - T_{\min}) \quad (1)$$

A uniform value of 2 kW/m^2 K for the heat transfer coefficient h_c, and a minimum temperature value, $T_{\min}$ of -170 °C were selected [5].

Table 1
Cryogenic cooling methods.

Pre-cooling	Spray cooling	Indirect cooling
Cooling of the workpiece	Cooling of the cutting zone	Internal cooling of the tool
		

Ding [6] and Hong [7] applied a similar procedure for modeling cryogenically cooled turning. Ding [6] presented the measurements of heat transfer coefficients for a cryogenically cooled hardmetal insert at different temperatures. These values form the basis for a thermal calculation of cooled turning, where the material-removal process itself is represented merely as a heat source. The heat flow during machining and the size of the contact zone were determined experimentally. For the cryogenically cooled insert, a surface-temperature-dependent heat transfer coefficient in the range of h_c = 23.3 kW/m^2 K for $T = -180$ °C to h_c = 46.8 kW/m^2 K for T = 650 °C at an ambient temperature of -196 °C (boiling temperature of LN2) was assumed. These very high heat transfer values are attributed to very intensive contact with the cooling medium based on the kinetic energy of the impinging jet, which destroys the insulating vapor layer as it forms [7].

2. New model for cryogenic cooling

2.1. Heat-flow model – boundary conditions

When drilling using monolithic drills with cooling channels, the cooling medium is introduced via the chuck and the cooling channels in the drill. If the used cooling medium has a significant

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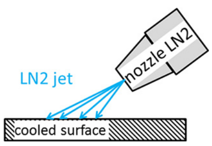
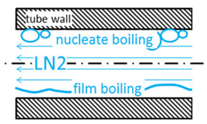
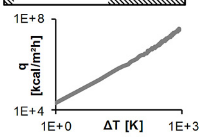
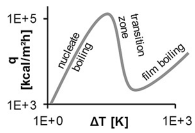
temperature difference to the drill temperatures during machining, there must be a description of these cooling processes in order to exactly describe the thermal behavior of the drill in the actual process. As mentioned above, the existing models focus on cryogenic cooling in machining free surfaces mainly in turning. These approaches cannot be applied to the cooling behavior in a tube because the gases produced cannot readily escape. A search for fundamental phenomena and applications of internal cryogenic cooling of tubes with LN2 led to models from physics. An approach specifically for cooling in a tube, which is based on a differentiation between nucleate boiling and film boiling, is presented, for example, by Fastowski [8]. With temperature differences between the tube wall and the boiling point of the liquid medium (LN2 → −196 °C) up to approximately $\Delta T \leq 15$ K nucleate boiling occurs, whereby individual gas bubbles are formed on the tube wall and carried along in the flow. At higher temperature differences, a continuous film of gas is formed on the tube wall, which is referred to as film boiling. A typical property of the gas film is its high insulation, which causes a sharp drop in the heat transfer coefficient. In addition to the gas properties and the temperature differences there is also a direct influence from the tube diameter. Thus the heat transfer coefficient for film boiling due to the formation of the gas film is described as follows [8]:

$$h_c = 0.62\frac{\lambda_m}{d_k}\left(\frac{d_k^3 Q_m (Q_{fl} - Q_m) g l_d}{\lambda_m \eta_m}\left(1 + 0.4\frac{c_{p,m}\Delta T}{l_d}\right)^2\right)0.25 \qquad (2)$$

where d_k is the tube diameter; Q_m, λ_m, η_m, Q_{fl}, $c_{p,m}$, l_d are material properties of the N_2 gas layer; g the gravitation.

Table 2 shows both approaches describing heat transfer in cryogenic cooling.

Table 2
Thermal models for cryogenic cooling.

Model	Spray cooling [6,7]	Tube cooling [8]
Application		
Heat-flow density q		
	$\Delta T = T_{wall} - T_{boiling, LN2}$	

The two approaches differ widely in their application and in the heat transfer coefficient. An accurate assignment of the models, especially in the drilling tool, is crucial for a realistic calculation of the heat distribution. Thus, the tube sections in the drill were modeled using the temperature-dependent heat-transfer coefficient of the tube-cooling model. In the simulation model, a reading of the local surface temperature was taken at each computational step followed by the calculation of the heat transfer value and ultimately the heat flow. At the outlet of the cooling medium, the formed gas film is discharged and there is a more intensive contact, which can be described by the spray-cooling model. Fig. 1 illustrates the combined thermal model for cryogenic cooling in the drill and shrink-fit chuck.

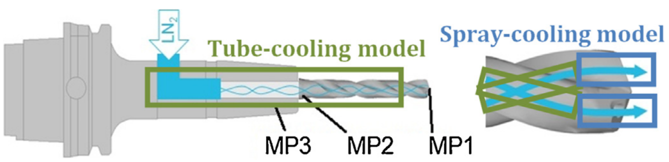


Fig. 1. The combined thermal model for cryogenic cooling in the drilling tool and the shrink-fit chuck.

2.2. Model setup and verification of the heat-flow model

The software DEFORM 3D V10.1 was used for the simulation of the cooling behavior at the drill and for the material-removal process simulation. For the calculation of the temperature distribution the drill was covered with a network of 100,000 FEs and the chuck with 150,000 FEs. Both components were assumed to be mechanically rigid. Thermal expansions due to temperature changes were assumed negligible, as these deformations were extremely slight in comparison to the degrees of deformation in the material-removal process. The heat transfer coefficient at the contact surfaces between the drill and the chuck was assumed to be 2.2 kW/m^2 K. In the first stage, the temperature distribution during cooling the tool and chuck was calculated and measured by thermo couples. Fig. 2 shows the test setup and the FE model, as well as the measuring points for verification of the model.

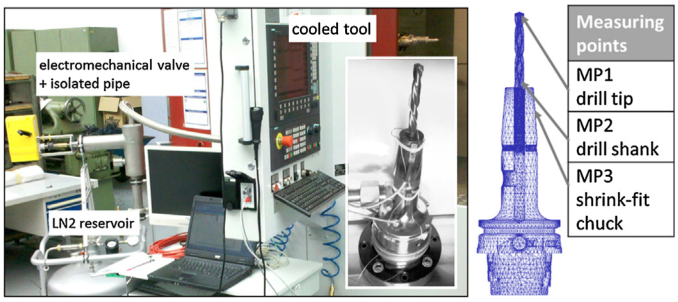


Fig. 2. Test setup and thermal simulation of the cryogenic cooling in drilling.

The measurement of the temperature profiles as shown in Fig. 3 starts with the opening of the valve on the coolant reservoir. This has an overpressure of 1.3 bar, which drives the coolant through the pipes to the connection on the chuck. The pipes, valves, chuck and drill are in a warm state (20 °C) at the start of measurement. The boiling cryogenic liquid cools these components while evaporating during the pre-cooling stage. This phase change is associated with a 645-fold increase in volume. Since the only option for venting this gas was through the two cooling holes in the drill, with only 1.2 mm diameter, the pre-cooling stage lasted for about 540 s before the cooling effect could be reached (Fig. 3). This first cooling phase was represented in the simulation by a continuously gas flow (h_c = 30 W/m^2 K for a strong gas flow). When the cooling effect of the LN2 reaches the drill tip (t = 0), the parameters for the cryogenic cooling (Sections 1.2 and 2.1) of the respective surfaces are taken to apply. As the experimental results and simulation show, there is significant cooling, especially at the drill tip.

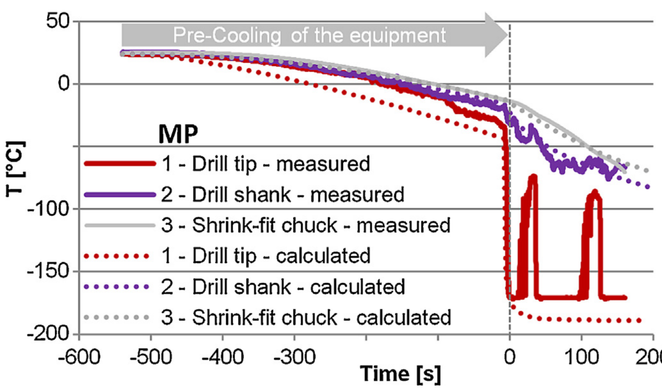


Fig. 3. Comparison of the calculated and measured temperature profiles during cryogenic cooling.

Temperatures as low as −189 °C were calculated. In the experiment, the temperatures at measurement point MP1 were about 15 K higher, since heat conduction by the stainless-steel protective sheath of the thermocouple caused erroneously high temperature values. This error was confirmed by measurements