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A REVIEW REGARDING COOLING TECHNIQUES IN THE TURNING, MILLING AND CUTTING PROCESS

BOGDAN NITA*, CAROL SCHNAKOVSZKY, RALUCA TAMPU, NICOLAE CATALIN TAMPU, EUGEN HERGHELEGIU

Vasile Alecsandri University of Bacau, Faculty of Engineering
**Corresponding author e-mail: nita.bogdan@ub.ro*

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Abstract: The aim of the paper is to present the actual state of techniques regarding the influence of cryogenic cooling in turning and milling process.

Processing some materials is impossible without cooling the tool or the processed material. Hard-to-cut materials are increasingly used in industry, so new methods of cooling these materials had to be researched. Cryogenic cooling is the most efficient method to cool down the turning, milling or cutting tools. There are a lot of materials that are not affected by the low temperature of the liquid nitrogen (LN_2), on the contrary, they behave better and have better proprieties after being cooled with LN_2. On the other hand, there are materials that do not behave very well after cooling them with LN_2 because their properties are changed, but with the right equipment, the amount of cooling liquid can be controlled, so that the temperature could be maintained at an optimal level.

This paper highlights the advantages of the cryogenic cooling systems compared to the classic cooling systems (cooling and lubricating in the same time) industrially used.

Keywords: LN_2, cryogenic, cooling, turning, milling, cutting.

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1. Introduction

Lately, numerous researches have been conducted for the optimization of the LN_2 cooling of the cutting tool for hard-to-cut alloys like titanium alloys [1], nickel-based alloy [2], hardened steel [3], inconel [4] or many others. These developments lead to the improvement of the process of hard-to-cut materials, which are used in aerospace industry, bearings, engine parts, nuclear applications and much more.

Friction and heat generation are the main problems in the turning operation. These two factors, which are closely related to each other, affect the tool life and the surface finishing quality, among other machining results [5].

Turning is the technological operation of cutting a material into a lathe. The main relative movement between the workpiece and the cutting tool is the rotational movement. Specific for turning, unlike other machining operations, is the rotation of the workpiece, not the cutting tool.

When manufacturing a part, the optimal processing parameters must be used, otherwise the material loses its proprieties and no longer meets the requirements for which it was made. To process a material under optimal condition we must keep the tool and the material at an optimal temperature and lubricated in order to obtain the best surface roughness.

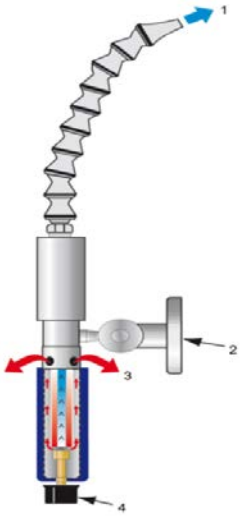
This paper highlights the advantages of the cryogenic cooling systems compared to the classic cooling systems (cooling and lubricating in the same time) industrially used. The cryogenic one is more complex and needs more study. We focused on that in order to achieve the best results.

2. Presentation and description of cooling systems

a. Cold air cooling method

The adjustable spot cooler is a low cost, easy to maintain, reliable solution for plenty of industrial cooling problems like short-time drilling or cutting materials. The temperature can be adjusted, manually, by turning a knob. It does not have any sensor or control of the output temperature. The adjustable spot cooler provides temperatures from -34°C to room temperature.

This spot cooler has a vortex cylindrical tube that converts compressed air from room temperature or even warmer, into cold air [6] (Fig. 1).



1- Cold air nozzle;
2- Swivel magnetic base;
3- Hot air exhaust;
4- Temperature control valve.

Fig.1. Adjustable spot cooler – mechanical schematics [7]

Usually it has one or more flexible tubes that hold the position to direct the air straight to the interest's point. A magnetic base gives us easy assembling and more important portability and also it has no moving parts and assures maintenance free operation. This can be used for cooling down the material before or after certain operations like drilling a whole or cutting a material for a short period of time. Because it uses just a jet of cooled air, the machined material heats and the jet of air can`t hold the temperature low, long enough to be machined in good conditions, in the case of a hard-to-cut material [6].

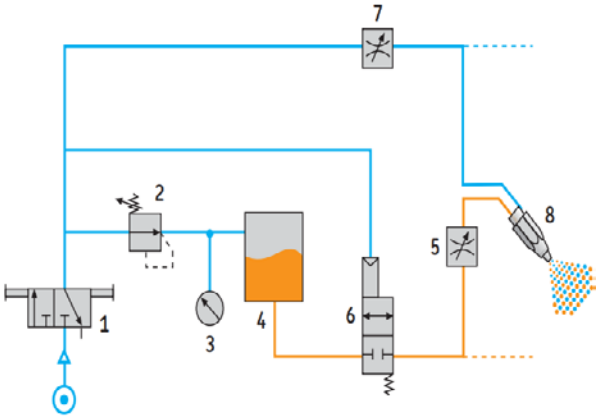
b. Cold lubricant cooling method

Another simple and cheap system, very good for lubricating the cutting tool and cooling it down is a system that uses vaporized oil (Fig. 2). This system is used in automotive manufacturing, where the materials are not as hard to process as those used in aerospace manufacturing.



a.

1- Pressurized air intake;
2- Spray nozzle;
3- Magnetic base;
4- Pressure control valve.



b. Mechanical scheme of the lubrication system

1- Hand slide valve;
2- Pressure control valve;
3- Manometer;
4- Storage container;
5- Oil adjustment screw;
6- 2/2 way valve;
7- Throttle;
8- Spray nozzle.

Fig.2. High pressure lubrication system [8]

The lubrication system has a reservoir with lubricant, one mixture adjustment and lubricant tubes with nozzles. Compressed air goes into the reservoir, and the lubricant is forced to escape thought the nozzles, where is sprayed in the form of vapors [9].

The aerosol required on the process spot is produced in the nozzle by the principle of Venturi. The air flowing to the oil outlet sweeps, whit the lubricant and turns it into extremely small lubricant particles. The concentric oil and air flow that results from the special design is keeping the jet from expanding, make the aerosol jet to be delivered directly to the process spot with maximum accuracy. The result, contamination of the surroundings with the excess aerosol is successfully prevented.

c. Liquid Nitrogen cooling methods – Mathematical modeling

The cryogenic treatment was proven to be enhancing the properties of some materials and also can improve the machinability of those materials [10].

In most of the cases cryogenic cooling occurs as an efficient effect for good performance machining. From all experiments made up to now, which included cryogenic cooling, the milling stability was seldom reported [2]. Most of the experiments leaded to higher stability limit compared with conventional milling operations, which indicates that the cutting efficiency can be improved greatly in LN_2 environment.

There aren't many cooling methods but some of them are more accurate and give better results with lower LN_2 consumption. The most used method is the one that sprays the LN_2 on the tool and the material in the area where it is processed. Most efficient one is the injection method, it isn`t easy to implement it but it has very good results [2].

Research has been done in the improvement of the machinability and tool life with the help of LN_2 cooling when processing nickel – based alloy. The LN_2 cooling still has negative effects on the performance of materials and tool, when the materials are cooled for a long time with high flow. Therefore, efficient control of the LN_2 jet is important for his cooling capacity and the processing costs [2]. LN_2 cooling methods are performed outside and not all the liquid is going to cool down the material, a small part of it evaporates same as the heat that dissipates in air and can't be measured with the temperature sensor. The higher heat produced would inevitably be absorbed in the atmosphere. Thus, the jet of the cooling liquid has 3 parts:

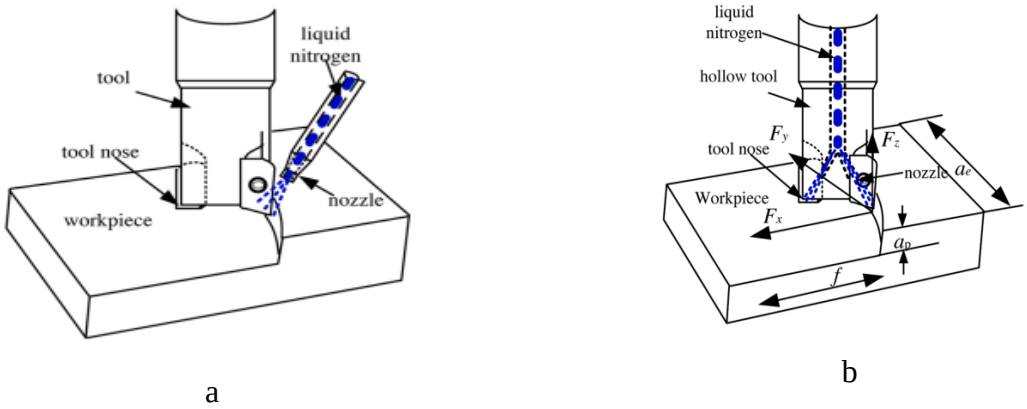
- one used for cooling the air,
- one cooling the cutting area and the tool,
- the third part evaporates from the surface of the workpiece [2].

The volume in the certain time can be described as:

$$V_{qf} = V_{an} + V_{wn} + V_{dn} \quad (1)$$

Where:

- V_{qf} – LN_2 volume of every tool cutting zone (L);
- V_{an} – the LN_2 the volume consumed in the air among the nozzle and the face of workpiece (L);
- V_{wn} – the LN_2 the volume of consumption in the cooling of the workpiece (L);
- V_{dn} – the LN_2 volume from workpiece surface (L) that escaped from the area.



a b

Fig.3. Liquid nitrogen sprayed (a)/injected(b) [2]

In the case of internal injection and external jet of coolant, the direction of the jet is the same as tool feed direction. The consumption of cooling liquid V_{qf} (L) of each tool is given by:

$$V_{qf} = q_f * t_z \tag{2}$$

Where:

- q_f – flow rate of LN_2 (L/h);
- t_z – advance time of tool (h);

$$t_z = \frac{1}{60\text{zn}} \tag{3}$$

Where:

- z – number of the tooth on the tool;
- n – speed of the spindle (r/min);

Here, Eq. (2) can be changed as:

$$V_{qf} = \frac{\text{q}_\text{f}}{60\text{zn}} \tag{4}$$

LN_2 it makes part of highly volatile liquids, and the cooling efficiency is based more parameters:

- time;
- distance;
- sprayed quantity.

The percept of operation is based on the Bernoulli equations and the persistence of the fluid. Meantime, the LN_2 flow rate can be determinate by:

$$q_f = \frac{5}{8} c_l A_c \sqrt{\frac{2gV_f(\rho_f - \rho_1)}{A_f \rho_1}}: \tag{5}$$

Where

- c_l – the flow coefficient $(0.02- 0.05)$;
- A_c – the float gap area (cm^2);
- V_f – the float volume (cm^3);
- ρ_f – the float density (g/cm^3);
- A_f – the float sectional area (cm^2);
- g – the gravitational acceleration (cm/s^2);
- ρ_1 – the cool fluid density (g/cm^3).

Similar, the amount of material that must cooled V_{mn} (mm^3) can relatively expressed by:

$$V_{mn} = \frac{\pi d_c}{z} * f_z * a_p \tag{6}$$

Where:

- d_c –tool head diameter (mm);
- f_z – the feed of every tool (mm/ z);
- a_p – the cutting depth(mm).

By the "Physical Thermodynamic Knowledge", the released heat Q_w (J) for nickel-based alloy cooled down in every tool feed can be defined by:

$$Q_w = c_w \rho_w V_{mn} * 10^{-9} * \Delta T_w \tag{7}$$

Where:

- C_w – the specific heat of GH4169 (J/kg·℃);
- ρ_w – the density of material (kg/m^3).

Because of the high feed rate the time of cooling is relatively short. Due to the low thermal conductivity of the alloy, the cryogenic efficiency in the direction of the cutting depth cannot be fully achieved in a short time [11]. If there are no energy loses we use the equation (Eq. 8).

$$\frac{dE}{dT} = -\lambda_w A_w \frac{d\theta}{dl} \tag{8}$$

Where:

- E – the energy that must be transferred, needed for cooling which is related to Q_w (J);
- λ_w – the thermal conductivity of cooled alloy (W/m·℃);
- l – the perpendicular distance of the cutting surface with the range of 0- a_p (mm);
- $d\theta$ – the temperature difference of two sections;
- A_w – necessary area of cooled alloy (mm^2).

Aw can be defined by:

$$A_w = \frac{\pi d_c}{z} * f_z * 10^{-6} \tag{9}$$

In Eq. (8):

- $d\theta$ can be measured by tests;
- E can be determinate as V_{wn}.

Minimum quantity of LN_2 needed can be determinate with:

$$V_{wn} = \frac{c_q \rho_w V_{nm} \Delta T_w}{C_p \rho \Delta T_N} = \frac{\pi c_w * \rho_w * d_c * f_z * a_p * \Delta T_w}{1000_z * C_p * \rho * \Delta T_N} \tag{10}$$

Where:

- C_p – the isobaric specific heat (J/kg ºC);
- ρ – the density of LN_2 in certain pressure and temperature (kg/m^3);
- ΔT_N – the modified temperature of LN_2 (ºC).

Because of the air and its capacity of thermal conductivity, between workpiece and nozzle, the jet of LN_2will be concluded by LN_2+N_2 in a limited area. The temperature and pressure in the

space affect in the same time the physical properties of LN_2+N_2 and the law of physics still is applied on the LN_2 [2, 5].

Here, the equations of the mass conservation and the impulse conservation are following radial and axial directions.

The equation of energy conservation of sprayed liquid nitrogen can be determined by:

$$\frac{\partial_\rho}{\partial_t}+\frac{\partial_\rho}{\partial_x}(\rho v_x)+\frac{\partial_\rho}{\partial_r}(\rho v_r)+\frac{\rho v_r}{r}=0 \tag{11}$$

- Equation of momentum conservation in axial and radial directions

$$\frac{\partial(\rho v_x)}{\partial_t}+\frac{1}{r}\frac{\partial}{\partial x}(r\rho v_x v_x)+\frac{1}{r}\frac{\partial}{\partial_r}(r\rho v_r v_x) = -\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(2\frac{\partial v_x}{\partial x}-\frac{2}{3}(\nabla\vec{v})\right)\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial v_x}{\partial r}+\frac{2}{3}\frac{\partial v_r}{\partial x}\right)\right]+F_x \tag{12}$$

$$\frac{\partial(\rho v_x)}{\partial t}\frac{1}{r}\frac{\partial}{\partial x}(r\rho v_x v_x)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_x)=-\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(\frac{\partial v_r}{\partial x}+\frac{\partial v_x}{\partial r}\right)\right]+\frac{1}{r}\frac{\partial}{\partial r}[r\mu(\frac{\partial v_r}{\partial r}-\frac{2}{3}\left(\nabla\vec{V}\right)+F_r \tag{13}$$

- Energy conservation equation

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial\rho}{\partial x}(\rho v_x T)+\frac{\partial\rho}{\partial r}(\rho v_r T)+\frac{\rho v_r T}{r}=div\left(\frac{\lambda_N}{C_p}\text{grad}T\right)+S_T \tag{14}$$

Where:

- t – working time, expressed by t_z (s);
- x – the axial distance with values between 0-l_2 (m);
- r – radial dimension which is the same as radial of nozzle head or the point where is cooled the surface of the workpiece (m);
- v_r – the radial velocity (m/s) being smaller than v_x in this case;
- v_x – the axial velocity (m/s);
- T – temperature on the work area (°C);
- λ_N – thermal conductivity (W/m·°C), →v being velocity vector,
- S_T – viscous dissipation of liquid nitrogen (°C·s^2/m^2);
- F_x – the axial spray (jet) force (N);
- F_r – the radial spray force (N);
- μ – the dynamic viscosity(N·s/m^2);
- p – pressure (MPa).

The flow speed of LN_2 in the nozzle v_n (m/s) can be expressed by:

$$v_n = \frac{qf * 10^{-3}}{\pi(\frac{D_n}{2})^2 * 3600} = \frac{9qf * 10^{-5}}{\pi D_n^2} \quad (15)$$

Where:

- D_n – the nozzle diameter for coolant (mm) that will affect v_r and v_x.

In the literatures we can find information about expressing the density and the isobaric heat capacity. The reduced Helmholtz energy that is associated with the reduced temperature τ and reduced density δ, results the equation:

$$\alpha(\delta, \tau) = \frac{a(\rho, T)}{RT} = \alpha^o(\delta, \tau) + \alpha^r(\delta, \tau) \quad (16)$$

Where:

- $\alpha(\delta, \tau)$ – the reduced Helmholtz energy (J/mol);
- $a(\rho, T)$ – the Helmholtz energy (J/mol);
- R – 0.2968;
- $\delta - \rho/\rho_c$;
- $\tau - Tc/T$;
- ρ_c – the critical density on acting surface (kg/mm^3);
- Tc – the critical temp. on acting surface (℃);
- $\alpha^\circ(\delta, \tau)$ – the ideal gas component (J/mol);
- $\alpha^r(\delta, \tau)$ – the residual part of the reduced Helmholtz energy (J/mol).

The Helmholtz energy mathematical theory, the equations (17) and (18) can indicate the isobaric energy capability of LN_2 C_t and density. The results show that ρ has more effect on p than T when the temperatures are lower.

$$p(\delta, \tau) = \rho RT \left[1 + \delta \left(\frac{\partial \alpha^r}{\partial \delta}\right)_\tau\right] \quad (17)$$

$$\frac{C_t(\delta, \tau)}{R} = -\tau^2(\alpha^o + \alpha^r) + \frac{(1 + \delta\alpha^r - \delta\tau\alpha^r)^2}{1 + 2\delta\alpha^r + \delta^{2\alpha^2}} \quad (18)$$

The temperature, pressure and density affect the dynamic viscosity μ (N·s/m^2). From Lemmon and Jacobsen models we can obtain the thermal conductivity and viscosity [12].

$$\mu(\rho, T) = \mu_0(T) + \mu_R(\delta, \tau) \quad (19)$$

Where:

- μ_0 – the viscosity of the dilute gas (N·s/m^2);

- $\mu_R(\delta, \tau)$ – the residual part (N·s/m^2).

From the table 1 we can obtain some data for LN_2, like:
- the dynamic viscosity and density depending of temperature and pressure;
- the density has opposite effects on N_2 towards LN_2;
- the viscosity degree of N_2+LN_2 mixture influences the cooling efficiency.

Table 1. LN_2 properties in different temperature and pressure [13]

	T/K	**p/MPa**	**μ/(m^2 /s)**	**ρ/(kg/m^3)**
LN_2	76.9	0.12	2.1	809
LN_2	93.8	0.55	1.3	724
LN_2	111.1	1.56	0.90	619
N_2	76.8	0.12	14.6	4.7
N_2	93.9	0.55	3.4	20.5
N_2	110.9	1.56	1.36	65

From equations (15)–(18) could be seen, the viscosity degree depends on temperature and density of LN_2+N_2 mixture, and is better at lower temperatures, but with the help of the conservation laws (11) and (14) lower temperature and high pressure will increase the escaped V_{dn}. The results showed that the better cooling effect was obtained at lower pressure and temperature [14].

If the pressure and the temperature increase than the LN_2 flow slows down, but the pressure and flow don`t necessary need to be high, in order to obtain the cooling effect. The internal injection can reach the lower pressure and temperature jet. The LN_2 efficiency ($\eta_{LN2)}$ can be expressed as the ratio between V_{wn} (Eq. 10) and V_{qf} (Eq. 4), in [13]:

$$\eta_{LN_2} = \frac{V_{wn}}{V_{qf}} = \frac{\frac{\pi C_w * \rho_w * d_c * f_z * a_p * \Delta T_w}{1000_z * C_p * \rho * \Delta T_N}}{\frac{q_f}{60_z * n}} = \frac{60\pi * n * c_w * \rho_w * d_c * f_z * a_p * \Delta T_w}{1000 C_p * \rho * q_f * \Delta T_N} \quad (20)$$

From Eq. (20) and fig. 4, we can observe that in order to obtain a specific lower temperature, nozzles need more liquid in the external spray system, compared to the inner injection. So the efficiency of consumption is lower for thinner injection system. Meanwhile, is continuously rising the effect between the nozzle and the point where the measurements has been made (cutting zone) fig. 4b. After the tests, results showed that a smaller diameter of the nozzle and a short distance to the cutting zone, leads to a better temperature (lower) [15]. In the case of external spray, the pressure needs to be higher with a bigger amount of LN_2 to reach the same temperature as inner injection (fig. 5). If the distance is smaller than 1mm, is easy to reach -190℃ in the case of inner injection. With the help of Eq. (20) the results of efficiency is not that good in external spray method. Based on V_{dn} resulted from Eqs. (11)–(14), it is a big amount for external spray but small for inner method, if we talk about the whole volume V_{qf}.

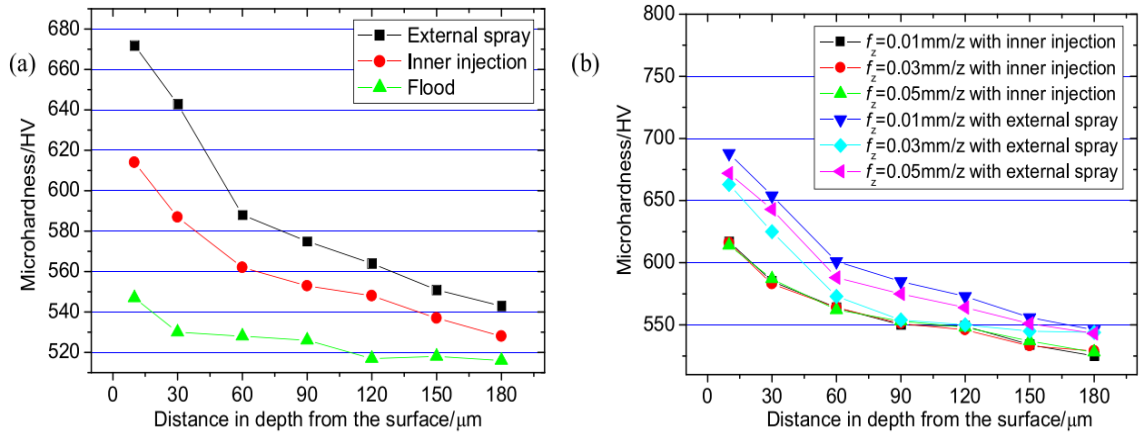


Fig.4. Micro hardness of the material [2]

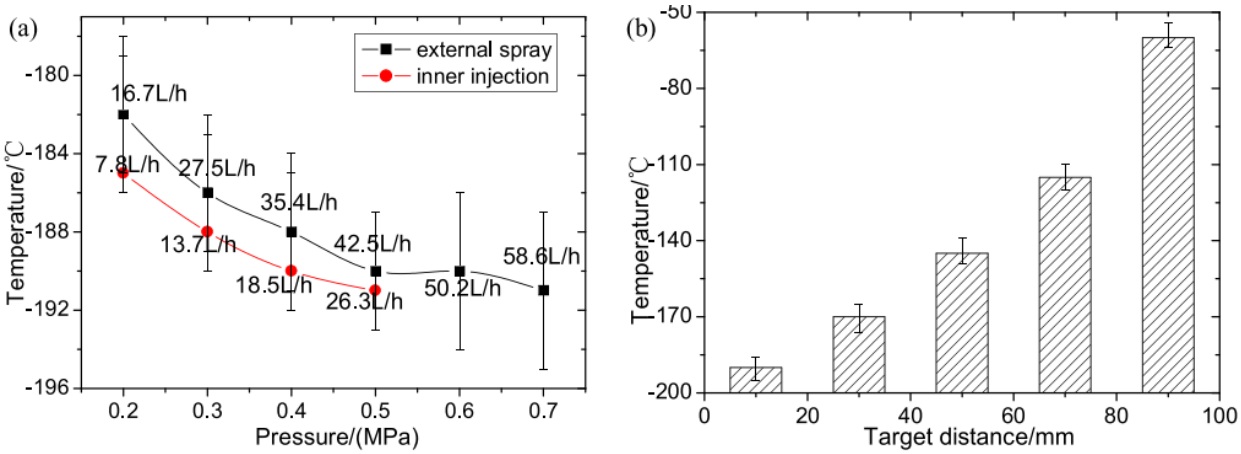


Fig.5. Fig. Cooling temperature measurements of nozzle.

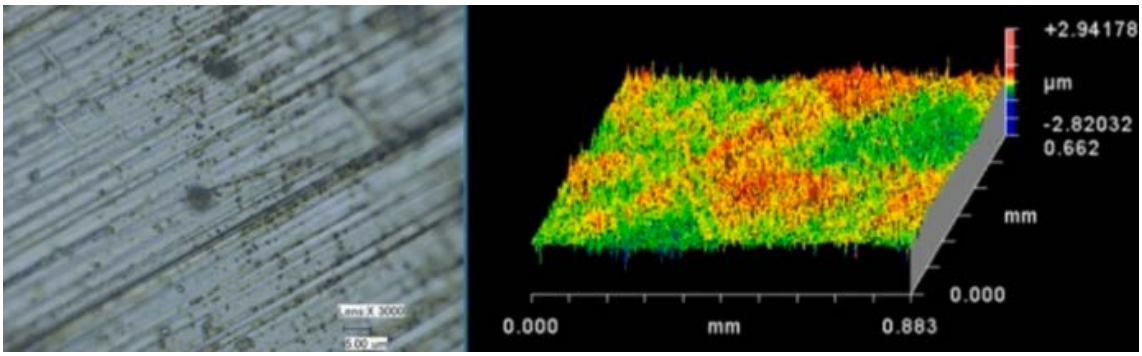
(a) Nozzle injection temperature at different pressures

(b) Injection temperature at different target distances (P = 0.5 MPa) [2]

Liquid nitrogen flow analysis

A few tests have been made to observe the surface of the material when machined with internal injection cooling and external spray method.

a.



b.

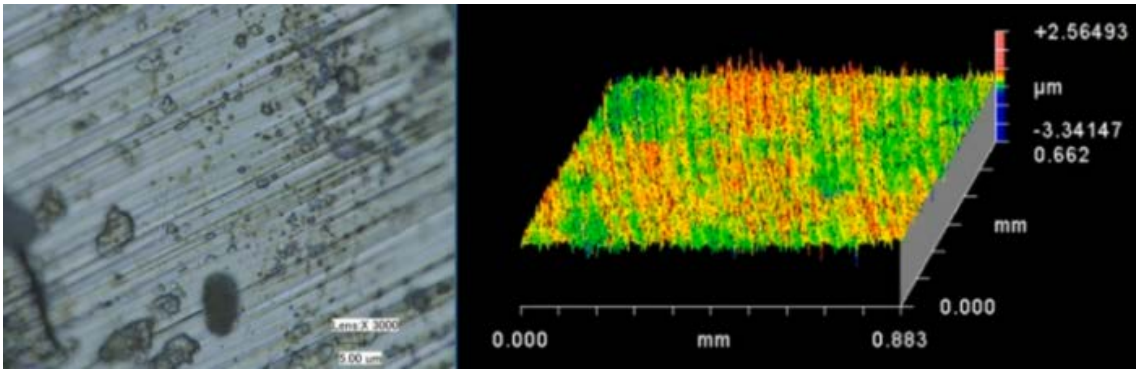


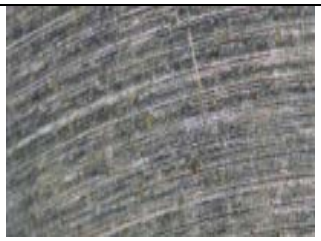
Fig. 6. The surface of material

We can see in the fig. 6a that the surface of the material was patchy, the roughness of the material was not exceptional. In fig. 6b we have the inner injection cooling method and compared to the external spray the surface of the nickel-based alloy was better. The roughness is better and from mathematical results and the test performed by Wang and Wang in their article, the micro hardness of the material is not affected, fig. 6b.

The literature presents cases where the cryogenic cooling can improve the machinability of hard-to-cut materials in certain conditions. In table 2 we can see that the plastic deformation given by the cutting speed is bigger [16, 17]. If the cutting speed is increased, the plastic deformation degree is getting smaller [11].

Table 2. Surface morphology of two cooling strategies [2]

	Cutting speed v_c/ (m/min)		
	75	150	200
External spray T=-190℃	 Ra 0.539µm	 Ra 0.351µm	 Ra 0.225µm

Inner injection T=-190℃			
	Ra 0.483µm	Ra 0.301µm	Ra 0.238µm

When the cutting speed is 150 m/min or more the temperature rises very fast. This is related to the poor thermal conductivity of the machined alloy and results in differences in the material roughness. After a certain point where the material starts to heat up the roughness it starts to increase as well. Here also we can talk about the high-frequency vibration from the cutting tool and its holder that is caused by the thermal softening of the material.

Also in table 2 we can see that the roughness of the material up to 150 m/min with the external spray method is higher than the inner injection one. At 200m/min the surface roughness seems to be smaller when the external spray cooling method was used because the quantity of LN_2 is bigger and can hold the temperature low. At 200 m/min the injection method can't hold the temperature low because of the small quantity of LN_2, this is why all the parameters like speed, vibration, alloy roughness and amount of LN_2 used at that specific moment, counts in the end result.

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