In-process generation of water ice particles for cutting and cleaning purposes

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In-process generation of water ice particles for cutting and cleaning purposes

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ABSTRACT

One of the disadvantages of pure water jet cutting or ablation is the relatively limited erosive capacity resp. cutting depth in harder materials (metals, ceramics, tougher plastics and so forth). The usual way to handle this is to add abrasive sand to the jet, resulting in a highly increased cutting performance. However, abrasives are not always desirable, e.g. when contamination with dusts has to be avoided. In addition, the abrasive particles only reach approximately 60% of the water jet's velocity due to friction and a limited acceleration process.

In order to address these issues, the authors have designed a process implementing ice particles as abrasive material. In order to achieve higher velocities using lower pressure levels, the process is based on an in-situ phase shift of the water jet immediately after having left the nozzle, which is obtained by precooling the water at 200 MPa down to -20 °C by means of a high pressure thermal exchanger.

The following text describes the current state-of-the-art, the proposed experimental setup, some preliminary performance analyses and prospects of further research.

1 NOMENCLATURE

\[\begin{align*}
d_{\text{nozzle}} & \quad \text{nozzle (orifice) diameter [mm]} \\
d_{\text{focus}} & \quad \text{focusing tube diameter [mm]} \\
p & \quad \text{water pressure [Pa]} \\
\text{HP} & \quad \text{high pressure (abbrev.)} \\
T_{\text{N2}} & \quad \text{temperature of N}_2 \text{ (l) under atmospheric pressure (const. = -196 °C)} \\
T_{\text{inlet}} & \quad \text{temperature of the high pressure water before the nozzle [°C]} \\
T_{\text{glycol}} & \quad \text{glycol temperature [°C]} \\
T_{\text{outlet}} & \quad \text{temperature of pressurised water after heat exchanger [°C]} \\
V_{\text{feed}} & \quad \text{jetting head traversal feed rate [mm/min]} \\
\end{align*}\]
2 INTRODUCTION

Recently, a number of research groups have been working on the substitution of the common mineral abrasive materials for abrasive water jet cutting by the use of ice particles. The available literature describes two different basic approaches to this task: Firstly the precedent preparation and storage of ice particles respectively ice pellets and the successive use in an entrainment jetting head, more or less comparable to the standard garnet based process; secondly, the in situ generation of ice during jetting by phase shifting the water from liquid to solid during the pressure drop downstream after the nozzle. This can be achieved f. e. by the entrainment of liquid nitrogen at -196 °C (or other cryogenic gases) so that the heat content of the process water is transferred to the N₂ solidifying the liquid and evaporating the gas, or by intensively pre-cooling the process water upstream of the nozzle in the high pressure regime.

An early publication has been done by Galecki et al. [1], dealing with the entrainment of pre-fabricated ice particles resulting in a substantial increase in the cutting efficiency regarding soft materials. Geskin, Li, Shishkin et al. published results of various experiments also based on the entrainment of ice pellets, but also of cryogenic gases [3-9]. Aluminium sheets of 3 mm width could be reliably cut with their system, although their main field of interest was cleaning and decoating.

Finally, Truchot et al. [2] have designed a setup based on a high pressure heat exchanger submerged in N₂ (l)-cooled silicone oil in an insulated basin. This allowed them to cool the pressurised process water upstream if the nozzle sporadically to a temperature level that reportedly resulted in a phase change of the water jet to an ice jet. Truchot stated that it was not possible to stabilise the process, so that his group was only able to maintain a solid phase jet for a few seconds and therefore could not achieve performance data.

Other low-temperature related jetting applications include systems by Laser Cutting NW and Flow Int. Corp (both Washington, USA) that use liquid nitrogen jets for both abrasive entrainment cutting heads as well as non-abrasive jetting for cutting of softer materials resp. cleaning / decoating purposes; however, water ice is not used as abrasive material by both setups.

In the experiments described below, the authors have addressed both of the two mentioned approaches to generate ice particles – entrainment of extremely cold liquefied gases, and pre-cooling the process water upstream of the nozzle.

3 EXPERIMENTAL SETUPS

Entrainment of cold liquefied gases

The following figure 1 outlines the basic principle of this method of generating ice particles in the jet.

A process pressure \( p = 360 \text{ MPa} \) was used to operate a standard water jetting sapphire orifice of 0.3 mm inner diameter with a 0.8 mm focusing tube of 76 mm length. The N₂ (l) was stored in a Dewar container and fed to the entrainment head by flexible silicone tubes. The cutting head was fixed to a 3-axis water jet cutting table.
Pre-cooling of high pressure water to achieve a spontaneous phase shift

The potential to generate solid ice jets by pre-cooling the liquid high pressurised water upstream of the nozzle is based on a specific characteristic of pure water. This quality is apparent in its phase diagram that is depicted in figure 2.

There is an absolute minimum in the liquidus line to be found at approx. 200 MPa corresponding to approx. -20 °C. In other words, accordingly pressurised water can be cooled down to this temperature before the nozzle without becoming solid and blocking the tubing. When the cooled water leaves the nozzle, the potential (pressure) energy is transformed into kinetic energy (jet’s velocity), i.e. the pressure is abruptly reduced to 0,1 MPa while the water’s temperature remains nearly at -20 °C (not taking into account...
dissipative effects in the nozzle). A phase shift from liquid to solid is the consequence. In the above diagram (figure 2) this process is depicted by the path marked by the heavy printed arrows.

For cooling the water, a high pressure heat exchanger was designed and built. The heat exchanger is able to cool a sufficient water flow to constantly operate a sapphire orifice of 0.1 mm inner diameter, or to operate bigger nozzles intermittently for limited time spans. The basic setup is pictured in figure 3.

![Figure 3: pre-cooling of pressurised water](image)

A high pressure tubing coil representing the secondary heat exchanger was submerged in an insulated container filled with a glycol solution (freezing point approx -45 °C). The glycol solution was chilled by a cold water aggregate to approx -30 °C (continuous operation) respectively to -20 °C (intermittent operation). The glycol solution was agitated by an electric stirring gear to optimise the heat transfer between solution and process water (see figure 4). In order to control the thermodynamic status of the system, the following temperatures have been monitored: $T_{\text{glycol}}$, $T_{\text{inlet}}$, $T_{\text{outlet}}$ (temperature of the glycol sole in the container, of the high pressure water before the heat exchanger, and of the HP water after the heat exchanger). Based on these measurements, the cooling capacity of the cold water aggregate was regulated.

![Figure 4: heat exchanger coil and stirring gear / container top lid](image)
The jetting head consisted of a single orifice nozzle fixed by a cap nut, and was operated by an experimental 1-axis CNC feed. All HP tubing after the heat exchanger including fittings and valves was insulated with a foamed elastomer coating.

Before the heat exchanger and the nozzle hand operated valves were installed to be able to shutdown the high pressure pump and at the same time maintaining the pressure within the coil to prevent ice formation in the HP tubing (until the sole temperature had increased to >0 °C).

**Specimens**

For both setups, specimens of AlMgSi1 (3.3215) of various thicknesses were used. The aluminium was soft annealed at 350 °C for 2 h and left to cool down in the oven over night to homogenise its mechanical properties and remove residual stresses.

**Measurement of generated kerfs / ablated volume**

The processed (i.e. jetted) specimens were then analysed to determine the geometry of the produced kerf. For this purpose, a stripe projection 3D surface scanner was deployed (manufacturer OMECA, type MicroCAD, combined phase shift stripe projection and greycode method, resolution x*y*z = 5 µm * 5 µm * 0.4 µm).

In other research projects of the authors, specifications to obtain reproducible kerf volume measurements have been developed including sequential steps of automatic alignment, filtering and cropping. These specifications have been used and allowed to reduce the measurement uncertainty for volumetric measurements to approx. +/- 0.01 mm³.

### 4 RESULTS AND DISCUSSION

**Entrainment of cold liquefied gases**

<table>
<thead>
<tr>
<th>Experimental parameters:</th>
<th>360 MPa</th>
<th>30 mm/min</th>
<th>0.3 mm</th>
<th>0.8 mm</th>
<th>1 mm</th>
<th>AlMgSi1 (3.3215)</th>
<th>N2 (l) @ atmospheric pressure, $T_{N2} = -196$ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure $p$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Traversal feed rate $v_{feed}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Nozzle diameter $d_{nozzle}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focus diameter $d_{focus}$</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standoff distance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entrained medium</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The first experiments produced some promising results that are pictured in the following figures 5 a-c. It is clearly to be seen that the cutting potential is significantly enhanced by the entrainment of liquid N₂:

Without nitrogen, the 3 mm aluminium sheet metal can not be cut reliably under the given process parameters, whereas with the addition of N2 (l) the plate is cut completely and reproducible.
However, the surface quality of the kerf is not comparable to an abrasive water injection jet cut (see figure 6). The surface features the matt and fibrous looking appearance that is typical for pure WJ cuts in metals; this indicates that the cutting mechanism is still based on an erosion process (more or less similar to pure WJ cutting) rather than on a micro chipping process as to be found when using standard garnet abrasive additives.

Due to a limited availability of the N₂ (l) infrastructure, the experiments regarding the entrainment of liquefied cryogenic gases have currently been ceased. A continuation of the experimental programme is currently under planning.

**Pre-cooling of high pressure water to achieve a spontaneous phase shift**

Experimental parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure p</td>
<td>200 MPa</td>
</tr>
<tr>
<td>Traversal feed rate v&lt;sub&gt;feed&lt;/sub&gt;</td>
<td>15 mm/min</td>
</tr>
<tr>
<td>Nozzle diameter d&lt;sub&gt;nozzle&lt;/sub&gt;</td>
<td>[0.1; 0.2, 0.3] mm</td>
</tr>
<tr>
<td>Standoff distance</td>
<td>[5; 10; 15; 20; 80; 125] mm</td>
</tr>
<tr>
<td>Specimen</td>
<td>AlMgSi1 (3.3215)</td>
</tr>
<tr>
<td>Water temperature</td>
<td>-20 °C +/- 1°C</td>
</tr>
</tbody>
</table>
The experiments conducted with the above described setup for pre-cooling the high pressure process water were separated into two steps: Firstly tuning of the hydraulic and thermodynamic parameters to obtain a stable process and to determine valid parameter ranges, and secondly using the jet to produce kerfs in the prepared aluminium specimens.

**Step 1: Process adjustments.** The capacity of the heat exchanger and of the cold water aggregate was designed to meet the requirements of a sapphire orifice type nozzle of 0.1 mm inner diameter under the condition of continuous operation. For this mode, the suitable glycol temperature was determined to approx -26 °C; this resulted in a HP water temperature directly before the nozzle of approx. \( T_{aq} \approx -20 °C +/- 1 °C \). A blockage of the system, i.e. formation of ice in the HP tubing was to be noticed when \( T_{aq} \) resp. \( T_{outlet} \) fell under approx. -25 °C for longer than a few minutes.

For the use of bigger nozzles, a glycol temperature of approx. -22 °C was used, and the setup was allowed to cool down with closed valves until the HP water in the heat exchanger coil and the glycol solution had identical temperatures. Afterwards the valves were opened, and jetting operations could be done until the chilled water stored in the coils was consumed and replenished by warmer water coming from the HP pump (this moment was identified by monitoring \( T_{aq} \)).

**Step 2: Cutting resp. kerfing experiments.** The first cutting experiments performed on aluminium sheet metal segments have unfortunately not shown any improvement of efficiency resp. cutting potential compared to a pure water jet. Various combinations of nozzle diameters and standoff distances have been used (see table above), but the achieved kerf volumes are identical under consideration of measurement uncertainties and statistical deviations.

Basically, two different causes for these results were identified: a) it could be the case that the acceleration process of the chilled HP water in the sapphire orifice dissipates enough potential energy to raise the temperature of the water after the nozzle to a level above 0 °C, and/or b) it is possible that the kinetics of the phase shift reaction after the orifice are not dynamic enough, i.e. the phase shift velocity is not sufficient to turn the liquid and supercooled water to a solid before hitting the specimen’s surface. These two issues have been addressed as follows:

*a) Dissipation of pressure energy and heating of the HP water to above 0 °C.* In order to investigate the effect of the nozzle’s efficiency, several nozzle designs were tested regarding their erosive potential with HP water at room temperature or slightly above compared to chilled HP water at -20 °C. These designs have included several orifice type nozzles without attached flow at the inner contour, and also nozzles with conical inlets and attached flows. Again, none of the nozzles showed a significantly improved erosive capability when operated with chilled water.

It is unfortunately not possible to simply measure the temperature of a high velocity water (or ice) jet, as any contact type thermometer will interact with the jet itself, transforming kinetic to thermal energy and thus falsifying any results. On the other hand, also IR based thermometry is not suitable as firstly the jet is permanently surrounded by a spray region hiding it from the optics, and secondly the emissivity of water (that is required to be known for exact IR based temperature measurements) is not easy to be determined either. Currently, the authors are working on simplified experimental setups to generate sufficient thermodynamic and hydro mechanical empirical data to formulate a finite volume simulation of the acceleration process itself, and possibly then being able to make accurate enough predictions of the jet’s temperature after the orifice.
b.) Too slow phase shift. In order to improve the speed of the phase shift after the nozzle, initial crystallisation nuclei in form of nanometre scaled soot particles have been added to the HP water. This was achieved by feeding a 1% solution of Degussa Derussol© A300 soot suspension to the high pressure pump (intensifier type). Unfortunately, also this measure showed to ameliorative effect, i.e. the erosive potential of the orifice nozzle used was not enhanced compared to chilled water without additives and to warm water.

Currently an experimental approach to finally determine the point of phase shift is under development. The central component will be a climate chamber in form of a PMMA tube (0.1 m diameter, 2 m length) with an approx. air temperature between 0 °C and 2 °C; within this chamber, the jet of super cooled water will be allowed to extend until finally completely disintegrated (i.e. without interaction with any surface and without being significantly warmed by the surrounding air), and the formation of ice crystals will then presumably be possible to be observed.

However, considering the above measurements and efforts, the results presented in the publication of Truchot et al. are despite the described improved experimental setup capable of continuous operation at $T_{eq} = -20 \, ^{\circ}C$ currently not reproducible.

5 ACKNOWLEDGEMENTS

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6 REFERENCES


