ICE JET TECHNOLOGY

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Ice jet technology also known as ice abrasive water jet (IAWJ) is a prototype technology currently under development. In IAWJ technology ice particles made from water are used instead of mineral abrasive. The aim is to increase the productivity of pure water jet (WJ) while keeping its advantages, producing no other waste product but water. Technology has great potential to be used in food and medical industries as well as other areas where cleanliness of the process and no additional waste product is of high priority. In order to use ice as an abrasive it has to be used at extremely low temperatures where its mechanical properties such as hardness become usable for machining applications. The paper presents the latest findings and achievements of IAWJ technology as well as the approaches and methodology used during its development. Two approaches to obtain ice particles in the water are studied, namely generation of ice particles in the cutting head during the machining process and generation of ice particles outside of the cutting head which are added to the jet similarly as in injection AWJ technology. The main challenge is to provide very cold and thus hard ice particles in the cutting zone where they are used as an abrasive and maintaining the system stability. It is therefore essential to monitor and control the temperatures occurring in the system. The presence of ice particles inside the jet could not be directly identified due to instrument limitations. Positive effect of ice on cutting efficiency was observed but could not be sufficiently studied due to instabilities present in the current state of the prototype.

KEYWORDS

IAWJ machining, IceJet, ice abrasive, cryogenic gas, ice particles

1 INTRODUCTION

Abrasive water jet (AWJ) machining process uses a high speed water jet for acceleration of very hard abrasive grains, enabling the removal of work piece material. The high speed waterjet is generated by pushing the water under high pressure, up to 600 MPa, through the water nozzle of a small diameter (from 0.08 mm to 0.4 mm) where the potential energy is transformed to kinetic energy, achieving supersonic speeds of the formed water jet. The process is universal as it is possible to machine almost any kind of material regardless of its composition, structure, hardness or other physical properties. This makes it possible to machine different materials that cannot be machined by traditional machining processes. AWJ machining technology has received considerable attention from several domains of production industry due to this competitive advantage.

In AWJ machining, the quantity of waste abrasive material produced is huge compared to the quantity of removed workpiece material. Handling of this sludge is usually not critical since abrasive material is non-toxic, but in e.g. disintegration of nuclear power plants the quantity of sludge plays an important role. Ice abrasive water jet (IAWJ) technology, also named IceJet, uses ice grains that melt away after the machining instead of mineral abrasive. The technology also has a great potential in both food and medical industries for applications, where the temperatures during cutting are desired to be as low as possible in order to prevent bacteria growth. Only by precooling the water under high pressure before the cutting head, the temperatures on the cutting front below 20°C [Jerman et al. 2015] can be achieved. It is expected that the machining capability of IAWJ technology will be between pure WJ and AWJ technology.

The water can be cooled below 0 °C at high pressures and still remain liquid, with its lowest temperature at -22.1 °C at the pressure of 215.7 MPa [Liu et al. 2009] as shown in the phase diagram of water in Fig. 1.

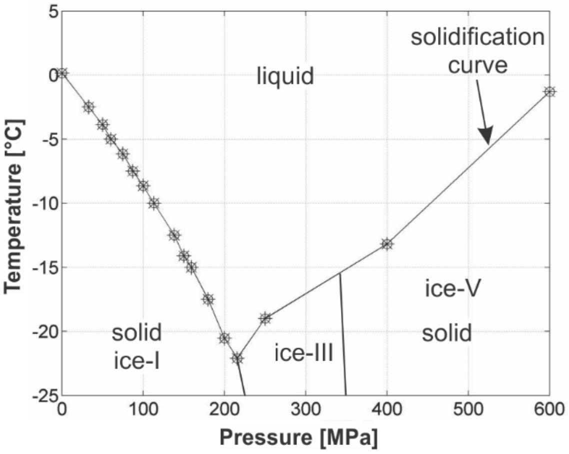

Figure 1. Phase diagram of water in the range of interest, plotted using data from [Linde 2005] and [Wagner et al. 1995)

In [Geskin et al. 1995] and [Truchot et al. 1991], the effectiveness of the use of ice particles as a substitute for mineral abrasives is demonstrated. Investigation on application of ice powder for material processing is reported as well [Shishkin 1999]. Among other the study involved investigation of water freezing and formation of water, ice and air jet stream for cutting and cleaning purposes. As reported by [Truchot et al. 1991], one of critical issues is that when ice particles come in contact with the surrounding air and relatively hot jet of water, they melt relatively fast. The temperature of the water jet is therefore a critical parameter that should be monitored and controlled. It is important to consider the temperature of ice particles, since mechanical properties (e.g. hardness) of ice particles and consequently machining ability are temperature dependent (Hobbs 1974). Generally, machining ability of ice particles increases with decreasing temperature.

Monitoring the temperatures at the inlet and outlet of the precooling system for in-process ice particle generation system is reported by [Jerman et al. 2015] and [Bach et al. 2010]. The water was cooled from 25 °C to 20 °C. The dynamic characteristics of an ultra-high pressure fine jet using the high speed camera was measured as well as the properties of droplets using the Phase Doppler Anemometry (PDA) [Wang et al. 2010]. It was discovered that at the pressure of 200 MPa and a water orifice diameter of 0.25 mm, the diameters of water droplets at the distance of 90 mm from the orifice range from 75 μm at the middle of the jet and 200 μm at the edge of the jet. This size is appropriate as the granulation of the most frequently use mineral abrasive of mesh #80 has in average the same size. This means that the bigger the droplet, the smaller the velocity of the droplet. For IAWJ technology utilizing in-process ice particle generation it is important to freeze slower and bigger droplets as they spend more time in the mixing chamber and therefore they are longer the contact with cooling media. Additionally, bigger droplets are at the edge of the jet and are therefore better exposed to the cooling media.

The other option is to generate ice particles outside of the cutting head in a suitable vessel and adding them to the waterjet in a similar manner as in AWJ technology. In this paper, both ice particle generation systems are evaluated. In both cases, water under high pressure, i.e. after the high pressure pump and before the cutting head was precooled to -10 °C. Further on, the areas of the main temperature build up were identified.

2 WORK METHODOLOGY

In order to perform the water temperature measurements on our IAWJ prototype, a custom made 2-axis AWJ cutting system was designed and assembled in the laboratory of the authors and is shown in Fig.2. It is equipped with a high pressure direct drive pump (P-2040, Omax, USA), with maximal pressure up to 280 MPa and flow rate of 3.2 l·min^{-1}. The cutting head (Allfi, AT) was connected to the high pressure pump using two high pressure pipe lines controlled by two 3-way valves V2 and V3 and a check valve V4, so that the water could be directed either directly to the cutting head or through the heat exchanger unit, positioned in between as shown in Fig. 3.

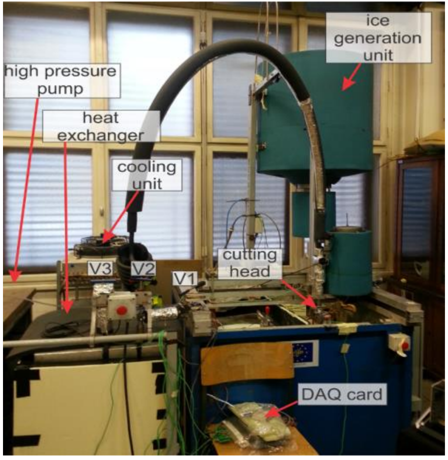

Figure 2. The experimental setup, showing the major components of the IAWJ prototype.

2.1 *Cooling system for high pressurised water*

A cooling compressor with 7.3 kW (Danfoss, SI) of cooling power was used to cool a glycol-water solution down to -25 °C. High pressure pipes where water flows from the high pressure pump to the cutting head were bent into a coil and submerged in the glycol. The temperature of the cooling medium was regulated in order to achieve the desired temperature before the cutting head. Pipes leading from the heat exchanger to the cutting head were thermally insulated using 20 mm thick insulating foam (Armaflex, Armacel, DE). Thermocouples were positioned as shown in Fig. 3 to monitor the temperatures.

2.2 *In-process ice particle generation*

In in-process ice particle generation, the ice particles are generated inside of the cutting head by injection of the liquid nitrogen into the mixing chamber of the cutting head. This approach was already studied [Shishkin et al. 1999], [Bach et al. 2010] and showed promising cutting results in cutting aluminium. We have addressed this issue by cooling the water under high pressure to the temperatures below -15 °C.

During the tests, the temperatures were measured inside the glycol water solution tank (TC7), on the collimation tube before the orifice (TC5) (Fig. 3) and in four positions on the focusing nozzle (Fig. 4). The parameters used during the tests were as follows: water pressure 200 MPa, water nozzle diameter 0.08 mm and focusing nozzle diameter 1.02 mm. Such ratio between the water and focusing nozzle were chosen in order to accommodate the gas phase generated during the evaporation of liquid nitrogen. For the same reason additional gas vent was made inside the mixing chamber.

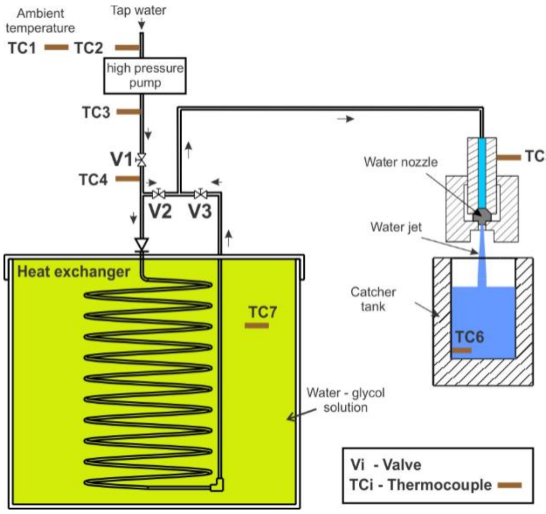

Figure 3. Schematic representation of cooling system for high pressurised water and position of thermocouples (TC).

2.3 *Ice particle generation outside the cutting head*

Ice particles are generated by freezing the atomized water droplets using liquid nitrogen. Water droplets are generated passing water and compressed air through 4 nozzles located at the bottom of the chamber (Fig. 5). To avoid the formation of ice blocks around the nozzles and thus to ensure the correct generation of water droplets, a heating system, which consist of a copper piece, two heating rods and a relay, are placed next to each nozzle (Fig. 6), which are activated when the temperature of the nozzles is below 30 °C. The nitrogen is introduced from the top of the prototype through a nozzle. When water droplets get in touch with nitrogen, they freeze and fall out of the chamber to be transported to the cutting head. A more thorough description of thermocouple installation is given in [Jerman et al. 2014].

In the literature, no data is available for the described method of ice particle generation, thus a broad range of process parameters was tested, namely air pressure from 0 to 2 bar and water flow rate from 0.5 to 10 l·h^{-1}. In all experiments, pressure of nitrogen added to the vessel was around 1.5 bar.

2.4 *Temperature measurements*

In order to measure and regulate the temperatures of different parts of IAWJ system, 1.5 mm thick K-type and 0.5 mm T-type class 1 thermocouples (TC) were used. The latter was used to measure low temperatures of the cooling medium, glycol (TC7 on Fig. 3). Thermocouples were connected to a 24 bit USB-2416-4AO data acquisition card (DAQ) (Measurement computing, USA), with 16 differential channels for thermocouple readings, all with cold junction compensation. The data from the DAQ were acquired and stored using software created in LabVIEW programming environment (National Instruments, USA). The positions of the thermocouples are shown in Fig. 3 and Fig. 4. A more thorough description of thermocouple installation is given in [Jerman et al. 2016].

Parameters of water pressure, water nozzle diameter size and cooling temperature were varied in order to determine their influence on water temperature in different parts of the machine as well as the waterjet temperature after the water nozzle. Three different water pressures of 200 MPa, 250 MPa and 280 MPa were used in order to determine how different pressure loads affect the temperature of water exiting the high pressure pump and the water jet temperature. According to the phase diagram of water (Fig. 1), the pressure of around 200 MPa is the pressure where the water can be cooled down the most. However, higher pressure is desirable in order to increase the productivity of the IAWJ, and for that reason two higher pressures were also chosen; 280 MPa being the limit for the pump used.

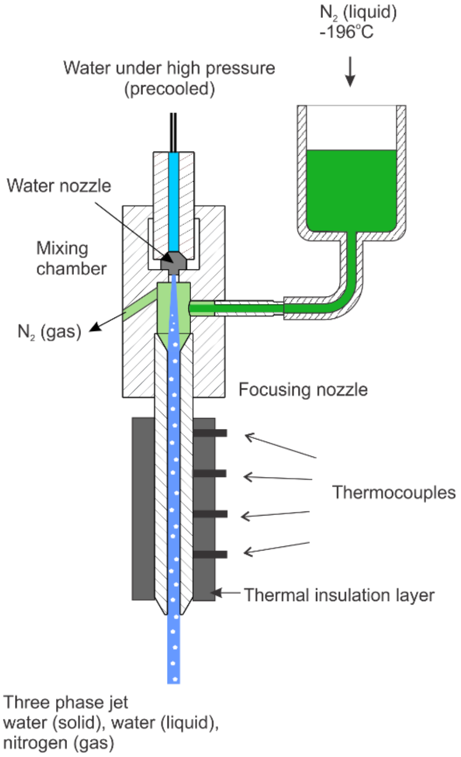

Figure 4. Setup for generation of ice particles inside the cutting head and the position of thermocouples to monitor the temperature in the focusing nozzle.

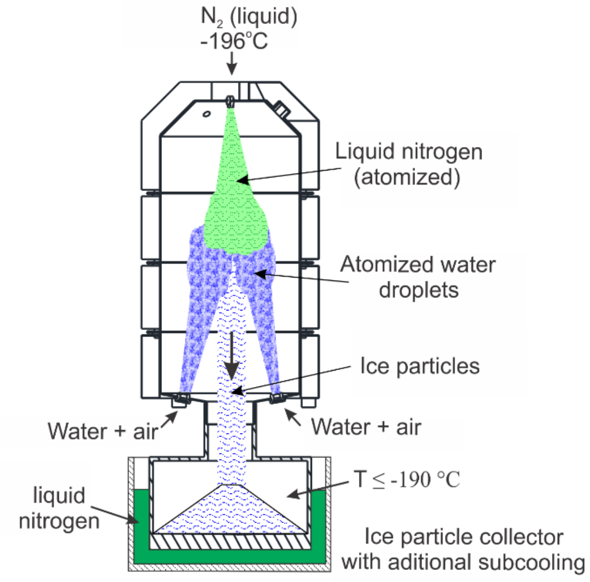

Figure 5. Schematic representation of the vessel for generation of ice particles outside the cutting head.

Figure 6. Vessel for ice particle generation with two copper heating rods and relays placed next to each water spray nozzle.

Two water nozzles with diameters 0.15 mm and 0.20 mm were used in order to determine the influence of nozzle size and water volume flow on the pump workload and the friction in the water nozzle, which influences the temperature of the high pressure water and the temperature of the generated waterjet. Nozzle velocity coefficient depends on the nozzle size [Annoni et al. 2008] and water pressure, thus both can affect the waterjet temperature.

Three different temperatures were set on the collimation tube in order to observe how the cooling of the water influences jet formation. For this reason, the temperature of the jet was measured with and without cooling, where the water temperature before the collimation tube was set to 0 °C and -10 °C. These values were selected in order to have a stable experiment for the selected pressures and nozzle diameters; otherwise, the water can freeze at lower temperatures using the highest pressure parameter.

The water temperature readings were acquired by running the IAWJ machine at each given parameter set. When the temperatures had stabilized, a minimum of 100 data samples were taken at the rate of 1 Hz, which were then averaged. Each set of experiments was repeated three times.

In order to evaluate the measurement results in the catching tank the temperatures at this point were also calculated analytically with respect to the temperature measured before the water nozzle. Temperatures in this area are of the most interest and deserve a more detailed analysis. Measurement results are compared with analytical results obtained through the following equations.

Theoretical velocity v_{th} of the water jet is derived from the Bernoulli equation:

$$v_{th} = \sqrt{\frac{2 \cdot p_0}{\rho_1}}, \tag{1}$$

Where p_0 is the water pressure before the water nozzle and ρ_1 is the density of the water after the nozzle for which 1000 kg·m^{-3} was used.

The velocity coefficient η of the nozzle gives the relation between the theoretical and the actual velocity of the jet v:

$$\eta = \frac{v}{v_{th}}, \tag{2}$$

Since the water jet is completely stopped in the catching vessel a total transformation of the jet's kinetic energy to heat is assumed:

$$\frac{1}{2}m\cdot v^2 = m\cdot c_p\cdot\Delta T, \tag{3}$$

$$\Delta T = \frac{v^2}{2c_p} = \frac{(\eta\cdot v_{th})^2}{2c_p} = \frac{\eta^2\cdot p_0}{\rho_1\cdot c_p}, \tag{4}$$

$$T_{cv} = T_n + \Delta T, \tag{5}$$

where *m* is the mass of the fluid, c_p is specific heat of the water (4200 J·kg^{-1}·K^{-1} was used) and ΔT is its temperature change. This temperature difference is added to the temperature of the water before the water nozzle T_n in order to calculate its expected temperature inside the catching vessel T_{cv}.

3 RESULTS

3.1 Cold waterjet

Results of the temperature measurements of cooling high pressure water before the cutting head are presented in Fig. 7 and Fig. 8. In Fig. 7 temperature profiles are presented at different thermocouple positions and different operational pressures, while in Fig. 8 relations between the input temperature and the one inside the catching vessel for the two nozzles at different pressures are shown. The latter are most relevant from the IAWJ point of view since ice particles are exposed to these conditions.

According to the results given in Fig. 7, the ambient temperature at TC1 has almost no effect on the final water temperature at TC6. The temperature of water entering the high pressure pump at TC2 has a small effect on the output temperature. This effect is further reduced with the length of the high pressure pipe. From the readings at TC3, which measures the exit temperature from the high pressure pump, a rise of 8 to 10 °C was recorded and was dependent only on the set pressure, rising by 1.5 °C for every additional 50 MPa. If the water is not cooled afterwards, then this directly affects the temperature in the catching tank. Thermocouple at pressure regulating valve V1 (TC4) shows a decrease of temperature for about 1°C caused by the heat exchange with surrounding air. Therefore the heat generated at the valve itself does not affect the temperature of the high pressure water.

The temperature of the cooling medium measured by TC7 was omitted from the charts for better clarity of the results. The temperature of the glycol solution was set to either -8 °C or -21 °C in order to achieve 0 °C and -10 °C respectively, before the water nozzle. The temperature in the catching vessel at TC6 remains almost the same for a given pressure and is independent of the used water nozzle diameter. Also, the temperature difference in the catching vessel for different water nozzles was found to be small and falls within the measurement uncertainty.

Fig. 8 shows the relation between the input and output temperature of the water before and after the nozzle. It can be seen that this relation is linear. In the case where the water was not cooled, some temperature fluctuations can be seen at the input temperature. These are due to several factors already mentioned above, the main one being the change in temperature contribution from the pump at different pressures. It can be concluded that the temperature in the catching vessel is affected by the pressure and the temperature of the water flowing through the water nozzle and not by the diameter of the nozzle. This is additionally verified if Eq. (5) is used to calculate the temperature difference. The measurements closely agree with the analytical values when the velocity coefficient of 0.90 is applied, as the maximum difference between predicated and measured values was less than 4 %.

The data analysis indicates that the main generation of heat occurs during water compression inside the high pressure pipe and inside the catching vessel. Cooling the water before the water nozzle proved successful and the recorded data show a linear relation between the water temperature entering the water nozzle and the one recorded inside the catching vessel. Linear temperature change in the catching vessel was also recorded for different pressures regardless of the nozzle diameter.

The temperature inside the catching tank turned out to be almost independent of the water nozzle size and was affected mainly by the water pressure and the temperature before the water nozzle.

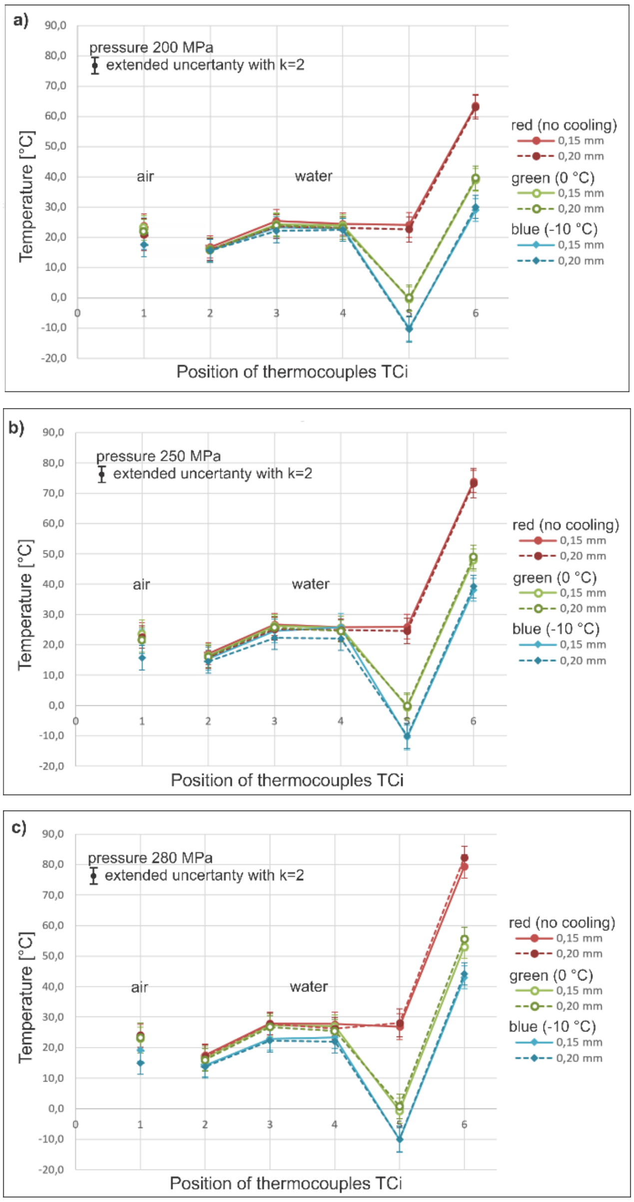

Figure 7. Temperatures of water measured at various positions and operational pressures. a) At water pressure 200 MPa, b) at water pressure 250 MPa and c) at water pressure 300 MPa

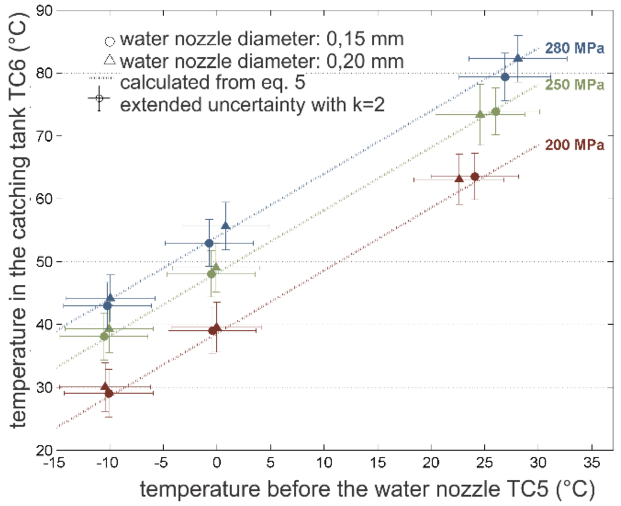

Figure 8. The relation between the input (before the water nozzle) and output (after the water nozzle) temperatures for different nozzle sizes and pressures used.

Temperatures measured in the catching vessel at 280 MPa are higher than those measured by thermographic camera on the surface of the focusing tube (results given in [Lebar et al. 2010], which used a 0.25 mm water nozzle at 300 MPa. In [Jerman et al. 2011] it was determined that the temperature on the focusing nozzle is indeed lower than that inside the catching vessel. This difference was attributed to the air entering the focusing nozzle through the mixing chamber, surrounding the jet inside. The bigger the difference between the water nozzle and focusing nozzle diameter, the bigger the temperature difference becomes as more cold air surrounds the jet.

The lowest temperatures recorded inside the catching vessel were 30 °C at 200 MPa and -10 °C before the water nozzle. The cutting head itself was covered with frozen condensed water and was therefore not heated significantly during the process due to friction in the nozzle. This leads to the conclusion that the jet itself also remains cold on the exit from the nozzle and that the friction in the nozzle has a small or negligible effect on the jet temperature. This result is expected, as the nozzle velocity coefficient is usually between 0.97 and 0.99 [Annoni et al. 2008]. It is assumed that the outer layer of the water jet heats up as it passes through the air due to friction, while the rest heats up inside the catching vessel where the kinetic energy gets transformed into internal energy. It is assumed that this is the reason why calculated values agree best when a lower than normal velocity coefficient of 0.90 is used as presented in Fig. 8. The temperature inside the catching vessel is assumed to be the similar to the one occurring on the cutting front and is important when cutting food or when used in medical applications due to potential bacterial growth.

The survival time of ice grain with 0.1 mm diameter, which was determined for a jet temperature of 40 °C, should increase significantly at -10 °C [Truchot et al. 1991], and even more if the ice grains are produced with diameters larger than 0.5 mm as proposed by for the injection method [Kovačević et al. 1997].

The temperatures in the jet core are low enough that ice crystals could be formed as suggested by [Truchot et al. 1991], but the mechanical properties of ice at these temperatures would not be very good in terms of efficient material removal [Bach et al. 2010].

3.2 *Ice particle generation*

When liquid nitrogen comes in contact with the warm waterjet it evaporates and removes the heat from the water, freezing it in the process. As the nitrogen evaporates however it increases in volume around 680 times. This creates a gas pocket inside the mixing chamber and prevents the liquid phase to flow inside. In this way the cooling capacity of the system is greatly reduced as the gas phase, while still very cold has greatly inferior cooling capabilities than the liquid phase. To assure the constant flow of the liquid phase we have created the gas release vent in the mixing chamber. In this way the excess gas phase can leave the mixing chamber through the vent and the liquid phase can flow continuously. Even though these measures were implemented, we could not repeat the results given in [Shishkin et al. 1999] and [Bach et al. 2010]. Thus, we did not continue the research in this direction, but we rather focus on mixing already prepared ice particles and the precooled water in the cutting head.

After a lot of experimentation with various process parameters in the vessel for ice particle generation we were able to produce ice particles with the average diameter between 0.5 and 0.6 mm. The histogram is given in Fig. 9. It is worth to mention that in order to avoid sintering of the ice particles the temperature of the vessel wall should be kept below -30 °C.

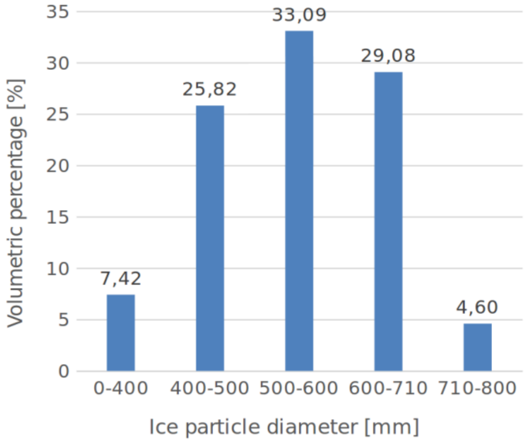

Figure 9. Histogram of ice particle diameters produced at carefully selected process parameters.

4 CONCLUSIONS

A holistic view on the IAWJ prototype machine is presented. The water temperature measurements on different parts of the system have been used to identify the places of heat generation.

While the heat generation on the cutting front cannot be avoided, the results show that cooling the water under high pressure lowers the jet temperature in a linear fashion. The water under high pressure is heated only during its compression in the high-pressure pump; afterwards, its temperature is changed (usually cooled) only by the heat exchange with the ambient air through the pipe walls. Flowing through the pressure regulating valve had no effect on the temperature. No heat generation in the water nozzle could be observed as it was covered with frozen condensation during the tests at -10 °C. The temperature can be lowered even further; however, stability of the process worsens when approaching -20 °C, especially when using water nozzles with smaller diameters as a result of lower flow rates.

It was found that water temperature is not significantly changed when passing through the water nozzle. If the water is cooled before the water nozzle, then the WJ temperature remains low as well, meaning that the ice particles could be formed inside. However, according to the revised literature, because temperatures are above -20 °C, the ice particles formed in such a way would not have adequate mechanical properties for machining purposes. This means that the direct phase transformation approach to generating the IAWJ would be inefficient. It is therefore advisable to cool the water only as a means to create better conditions for the injected ice abrasive.

Among others, IAWJ technology has great potential in the food and medical industries for applications, where the temperatures during cutting are desired to be as low as possible to prevent bacteria growth. The results show that cooling the water could bring the temperatures on the cutting front below 20 °C if water is precooled before entering the water nozzle.

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