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Paper

MEASURING THE WATER TEMPERATURE CHANGES THROUGHOUT THE ABRASIVE WATER JET CUTTING SYSTEM

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ABSTRACT

In this paper we present the measurement of temperature changes in the abrasive water jet (AWJ) water system using the thermocouples. Temperatures of water throughout the whole AWJ system from the water supply to the cutting head will be measured. The purpose of this research is to gather temperature data of the water system. The data will later be used to evaluate the results produced by the thermodynamic computer model of the Ice Jet (IJ) system, where the mineral abrasive of the conventional AWJ system is being replaced by the ice particles. The particles are generated inside the mixing chamber of the cutting head by partial transformation of the high speed water jet into ice particles. This is accomplished by injection of the cryogenic gas into the mixing chamber. The temperature control of the water entering the mixing chamber is therefore essential for the control of ice generation. The data will also be used to design and control the cooling system of the high pressure water which is also a part of the IJ research.

Keywords: AWJ, temperature measurement, ice particles, cryogenic gas, ice jet

1. INTRODUCTION

Abrasive water jet (AWJ) uses a high speed water jet for accelerating very hard abrasive grains and thus enabling the removal of workpiece material. 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 new materials which 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.

Many industrial processes and specifically the AWJ machining, produce waste that is in the form of sludge in which waste material is mixed with water. The quantity of abrasive material produced in the waste is huge in the comparison to the quantity of residuals of workpiece material. Handling of this sludge is usually not critical since abrasive material is non-toxic, but in some applications the workpiece residuals can be harmful to the environment.

One of possible solutions is to substitute abrasive particles in AWJ with ice crystals and thus get rid of the majority of material in the waste sludge. The idea of Ice Jet was already tested as several authors reported [1-4] but several issues are left to be solved.

Previous experiments from the research done by Geskin et al.[1], Truchot et al. 1.[2], demonstrated the effectiveness of the use of ice particles as a substitute for abrasives. The principal shortcoming of WJ is the low efficiency of the energy transfer between the jet and the work piece. The energy efficiency of AWJ is still low although acceptable.

In his thesis, Shiskin [3] investigated the application of ice powder for material processing. 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. [2], one of critical issues is that when ice particles come in contact with the surrounding air and relatively hot jet of water, they are melted too fast. The temperature of the water jet is therefore a critical parameter that should be monitored and controlled. In the work presented in this paper, we wanted to discover the areas where the main temperature build up occurs and the degree of heat contribution that this area has. The latter is the most important part of the research. This data will later be used to design a system for cooling either the water under high pressure or the high speed and to validate the computer model of the temperature distribution in the cutting head.

Ice particles in the high speed water jet can be generated based on two different principles. By the first principle water jet can be either partially frozen by addition of liquid nitrogen at -196ºC into the mixing chamber and so partially freeze some part of water droplets surrounding the high speed water jet. By the second principle ice particles are generated outside of the mixing chamber and are then injected in the water jet in nearly the same way as conventional abrasive. In both cases it is important to consider the temperature of ice particles, since mechanical properties (e.g. hardness) of ice particles and consequently machining ability is as explained by Hoobs [5], temperature dependent. Generally machining ability of ice particles increases with decreasing temperature. In order to know more on the temperature situation in the cutting head and below this experimental study of temperature situation has been initiated and reported upon in this paper.

Kovacevic et al.[6] and Mohan et al. [7] studied the temperature distribution in the AWJ focusing nozzle in order to monitor the wear of the nozzle. They have used an infrared thermography method. Kovacevic et al. measured the temperature distribution for three differently worn focusing nozzles. They established two things. First as the nozzle diameter increases the peak temperature decreases, and second the position of the peak temperature moves toward the nozzle exit as the diameter of the nozzle increases. This shows where the wear is most emphasized during different stages of the nozzle wear.

Liu and Schubert [8] measured the temperature on the focussing nozzle although not on the ordinary system but on Flash AWJ in order to control the temperature of the water at piercing of different materials by Flash AWJ system.

Bach et al. [4] monitored the temperature at the inlet and outlet of the pre-cooling system for their in-process ice particle generation system, where they cooled the water from 25 ^{o}C to -20 ^{o}C. Based on presented background and our preliminary experiments experimental setup was built in order to test the influence of pressure and geometrical parameters of cutting head on water temperature change.

In further experiments the high pressure water will be cooled down to different temperatures below 0 ^{o}C. This is possible due to the property of water that its freezing temperature drops with high pressure [5]. Also a numerical model of the temperature distribution inside the cutting head is going to be created. The test procedure described in this paper will be used to monitor and control the cooling system and to verify the numerical model mentioned above.

2. EXPERIMENTAL SETUP

Changes of water temperature were measured in several parts of the AWJ system as it is shown in **Figure 1**, from the pump to the exit from the focusing tube and also in the water intercepted downstream of focusing tube. Due to the extreme circumstances a direct measurement of the high pressure or high speed water temperature was impossible. Therefore the temperatures were measured indirectly using K- type thermocouples. In this way we do not get the direct temperature values but the temperature contribution from different parts of the AWJ system. To measure the water under high pressure thermocouples were set up in such a way that they were in contact with the surface of the high pressure tube. The contact area was insulated with a 15 mm thick and 150 mm long Armaflex insulation foam manufactured by Armacell (Germany) and a layer of aluminium foil. This provided static conditions on the place of contact. The temperatures of the high speed water after the orifice were measured indirectly on multiple points. In the mixing chamber the thermocouple was positioned adjacent to the jet of water. Temperatures along the focusing tube were measured by inserting the thermocouples into the blind holes that were eroded into the nozzle 0.3 mm from its inner wall and placed 15 mm apart. The whole nozzle was than insulated using a nylon cylinder and sealed with silicon on both ends of the cylinder.

For the experimental work a 2-axis OMAX 2652A AWJ cutting system (USA) was used, equipped with a high pressure intensifier pump BHDT Ecotron 403 (Austria). Three different pressures 100 MPa, 200 MPa and 300 MPa were used during the experiments in combination with orifices with two different diameters of 0.1 mm (V2) and 0.25 mm (V1) and the focusing nozzle of 1 mm (F1) of diameter all manufactured by Allfi (Austria). Different pressures and diameters were selected to observe the effect that one of the parameters has on the temperature of the water on different parts of the AWJ high pressure water system.

To measure the temperatures 1.5 mm thick K-type thermocouples were connected to a USB-2416-4AO data acquisition card (DAQ) manufactured by Measurement computing (USA). This 24-bit DAQ has 16 differential channels for thermocouples readings, all with cold junction compensation and using a sample rate of 4 Hz. The card was calibrated just prior the experiments were executed to provide more accurate readings from the thermocouples using an auto calibration function of the card. The data from DAQ was acquired and stored using a program created in a LabVIEW program package. Different positions of the thermocouples are shown on **Figure 1**.

The first thermocouple (TC 1) was used to constantly measure the ambient temperature. The second thermocouple (TC 2) was used to measure the temperature of the tap water that is entering the high pressure pump. This was performed by submerging the thermocouple into the stream of running water for a long time in order that the readings stabilized and the running water reached its lowest temperature. The water temperature on the exit from the high pressure pump (TC 3) was measured indirectly on the surface of the high pressure pipe of 3/8’’ diameter. For a better contact the heat conductive thermal paste was used and the whole spot was thermally insulated using a 10 mm layer of Armaflex covered further by a layer of aluminum foil (**Figure 1 b**). At TC 4 the temperature was measured just before entering the cutting head using the same method as with TC 3, with the difference that the high pressure tube on this point measured ¼’’ in diameter. This part was additionally insulated from backsplash water using a PVC foil. The length of pipe from TC 3 to TC 4 was 5 m. At TC 5 the temperature inside the mixing chamber was measured through a hole in the side of the mixing chamber. The thermocouple was positioned adjacent to the high speed water jet. On the place of abrasive inlet hole the surrounding air was allowed to get sucked inside. For TC 6-9 the temperatures on four different spots along the focusing nozzle were measured on a distance 0.3 mm from the inner wall of the focusing nozzle. At TC 10 the temperature of the high speed jet of water was measured by capturing it in the thermally insulated tube filled with water (the catching vessel), which was then replaced by the water of the jet. The thermocouple was used to measure the temperature of this water and measurements were recorded when the temperature gradient reached zero, which meant that the initial water was replaced or heated up by the high speed water of the jet. Because the volume flow of water is much smaller with the smaller orifice, two such vessels with different volumes were used, one with 3 dm^3 and the other with 1.5 dm^3. The TC 11 thermocouple was used to measure the temperature in the insulation layer of the vessel.

2.1 Experimental results and discussion

The data was acquired by running the machine at different pressures and different nozzle combinations. When using the bigger catching vessel the time it took for the temperature on TC 10 to stabilise was around 10 minutes while with the smaller vessel this time was around 5 minutes. The bigger vessel was used in combination with the bigger orifice while the smaller one was used with the smaller orifice. This was done because the volume flow of water was lower with the smaller orifice and it would take longer for the temperature gradient to reach zero. Water flows at different parameters are shown on **Table 1**.

The data presented on the charts was averaged to compensate for the noise that occurred during the measurements. For the readings of thermocouples 1-9 this was done on a case of a larger number of samples (1000) since the temperatures on these points stabilized relatively quickly. The temperature readings from TC 10 and 11 were averaged for the last 5 seconds of the measurement where the temperature gradient was close to zero. When taking the readings at different pressures we could observe the increase in the level of noise in the signal on thermocouples TC 1-9. This could be explained with vibrations that get bigger at higher pressure which interfered with the readings from the thermocouples attached to the system as well as with possible electrical interference. Vibrations could have caused the thermocouples to temporary lose contact with the surface, giving the false reading. The signal got stable in the instant the pump was turned off.

On **Figure 2-4** we can observe that for each given pressure the temperature difference for different orifices is very small except for the temperatures on the focusing nozzle where the temperatures are smaller in the case of a smaller orifice. This is explained by the fact that on focusing nozzle the increase of the temperature is due to the friction between the water jet and the inner wall of the nozzle while in the case of the catching vessel, the increase of temperature is due to the fact that air inside of the focusing nozzle is giving us lower temperature readings. It is also possible that some additional temperature rise can be caused by transformation of kinetic energy of water jet into the internal energy of the water. This explains that on the place of TC 10 the temperature is dependent only on the pressure and not on the configuration of nozzles. When using the smaller orifice the volume flow of water was smaller, this meant that it took longer for the V2F1 configuration to heat up the water inside the catching vessel.

Figure 5 shows the temperature profile for orifice 0.25 mm and focusing nozzle 1 mm at different pressures. Temperatures from thermocouples 1-5 are virtually identical. The main difference begins to show itself on the thermocouples 6-10 placed the focusing nozzle and inside the catching vessel. The temperature gradient along the focusing nozzle is very linear with the correlation factors $R^2_{100MPa,V1}$=0.98, $R^2_{200MPa,V1}$=0.99, $R^2_{300MPa,V1}$=0.98. Temperatures along the focusing nozzle are rising relatively proportional to the pressure used.

Figure 6 shows the temperature profile for 0.1 mm orifice. The nozzle reduces the flow rate of water thus the temperatures along the focusing nozzle are generally lower compared to those from the bigger orifice at the same pressures which is due to the lower friction between the water and the nozzle. The same as with the bigger orifice, the temperature gradient is again very linear along the focusing nozzle with the correlation factors $R^2_{100MPa,V2}$=0.96, $R^2_{200MPa,V2}$=0.99, $R^2_{300MPa,V2}$=0.91.

3. CONCLUSION

Based on results from experiments we have a relatively good idea about how much the different parts of the AWJ system contribute to the temperature of water even though the temperatures on most points were not measured directly. The contribution from the high pressure pump is around 15 ^{o}C regardless of the pressure used. The drop of temperature along the pipes is higher with lower pressures since the speed of water is much higher at higher pressures which means less time for the heat exchange with the ambient. The temperatures measured inside of the mixing chamber were very low and even though they were higher with the higher pressure, the recorded low temperatures are probably the consequence of the ambient air being sucked into the chamber. The readings from this point will be more significant when the liquid nitrogen will be injected through the abrasive inlet hole. Interesting is the drop of temperature in the beginning of the focusing tube when smaller orifice was used. This can again be explained by the fact that with the smaller orifice, more of ambient air can be sucked inside of the focusing tube. After this point the temperature gradient along the focusing nozzle was in all combinations very linear with similar temperature gradients for a given pressure for both orifices. The temperature inside of the catching vessel turned out to be almost the same with both orifices and was dependant only on the water pressure. For each 100 MPa rise of the pressure the water got hotter for around 15-20 ^{o}C. The temperatures measured along the focusing nozzle with the 0.25 orifice at 300 MPa in this paper are also comparable with those measured by Lebar et al. [9], using a IR camera with the same orifice and a focusing nozzle of the same length but 0.8 mm in diameter. The thermo graph from that research is presented on **Figure 7**.

Measuring the water temperature in the way presented in this paper proved to be more difficult at higher pressures since the conditions got more extreme. The vibration caused a lot of noise in the recorded signal especially in the focusing nozzle. Catching the high speed water jet inside of the small vessel at 300 MPa proved to be challenging since the jet has a lot of energy and it was difficult to contain the water.

The research gave us information for further work on the Ice Jet project where the temperatures using the precooled water and cooled down focusing nozzle will have to be controlled. The data collected will also be useful for comparison with the numerical model that will be created.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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6. GRAPHICS

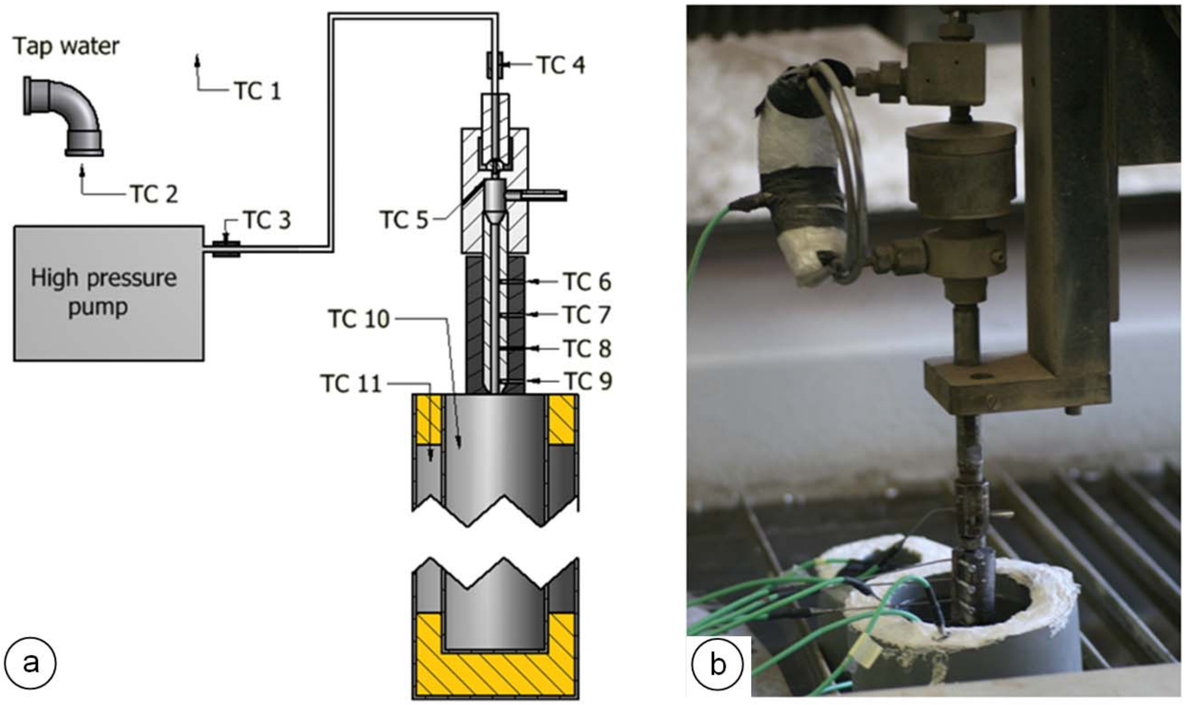

Figure 1. A schematic representation of experimental setup (a) and situation on the AWJ machine (b).

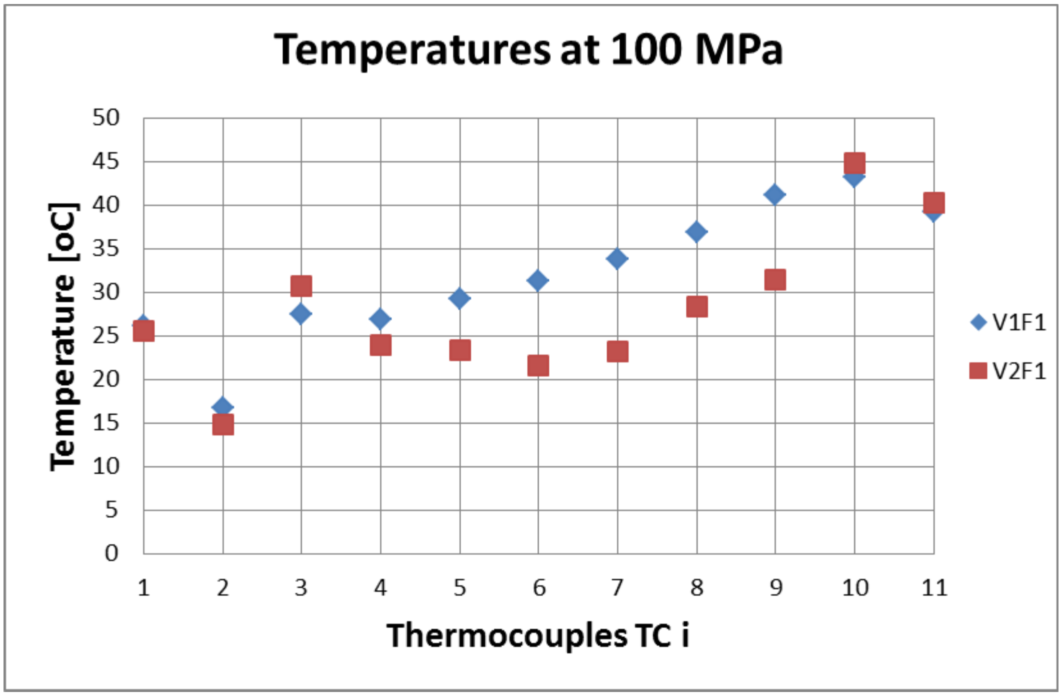

Figure 2. Temperatures measured at 100 MPa.

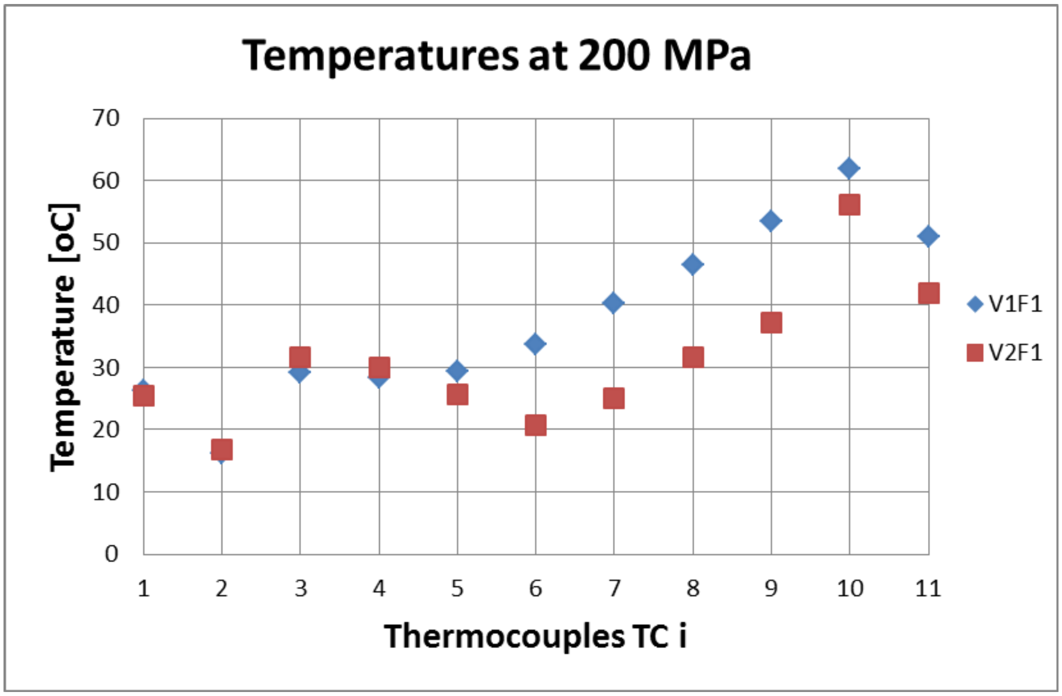

Figure 3. Temperatures measured at 200 MPa.

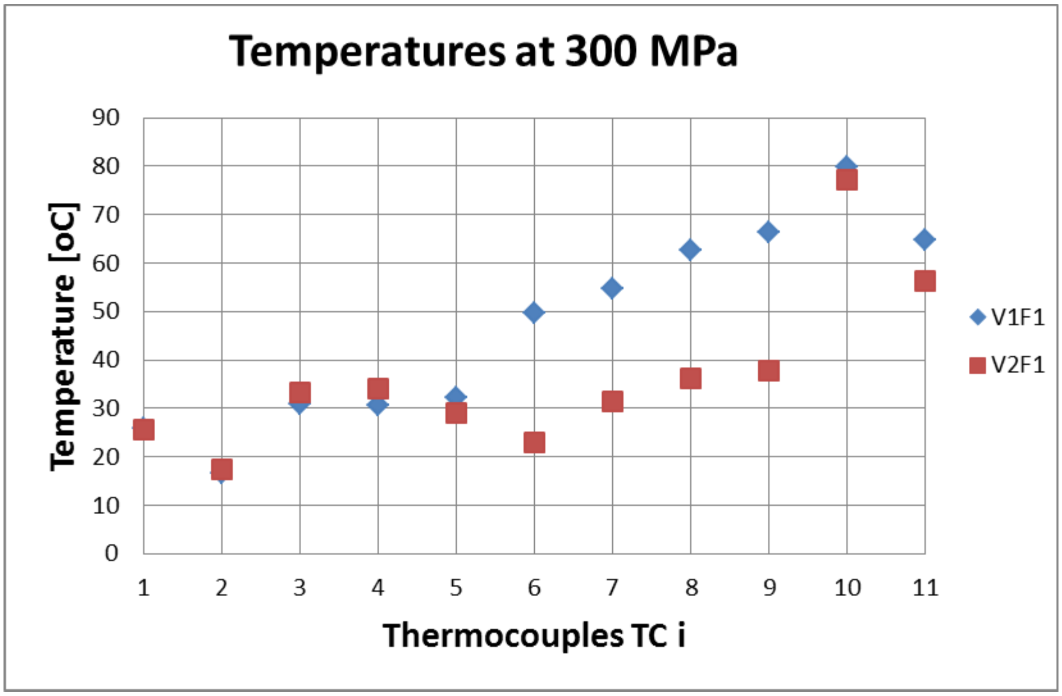

Figure 4. Temperatures measured at 300 MPa.

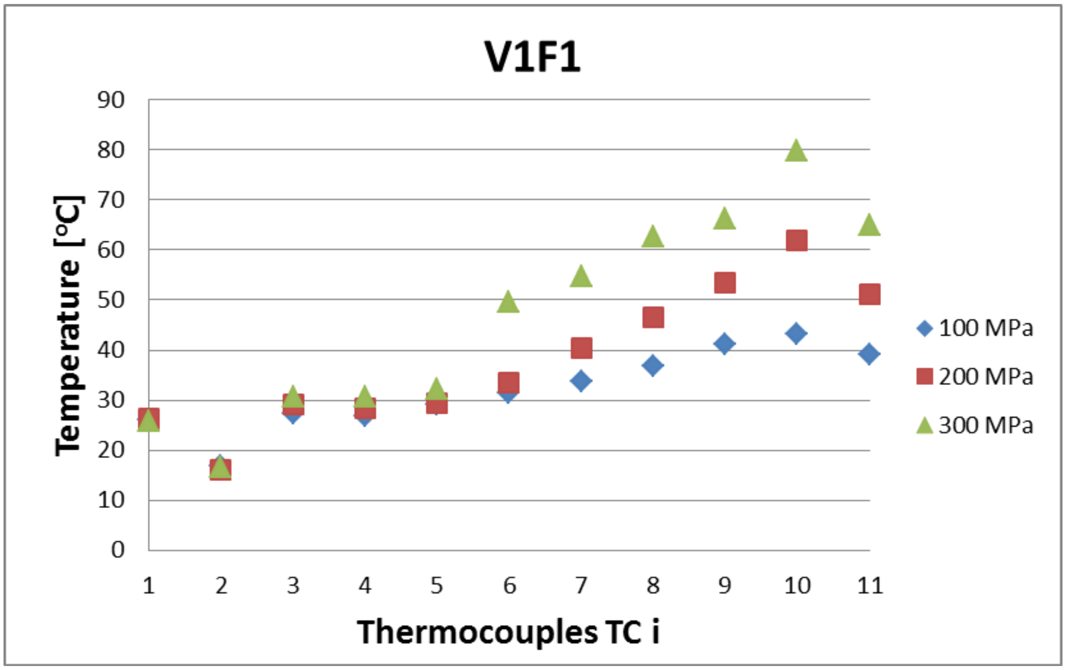

Figure 5. Temperatures at different pressure for the 0,25 mm orifice and 1,02 mm focusing nozzle.

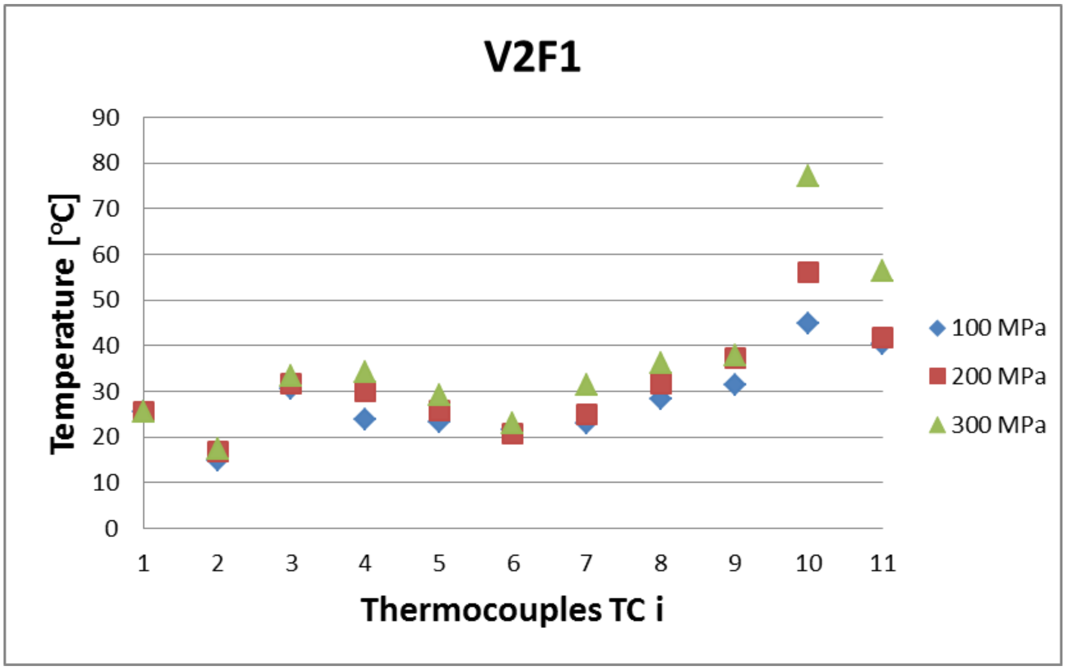

Figure 6. Temperatures at different pressure for the 0,10 mm orifice and 1,02 mm focusing nozzle.

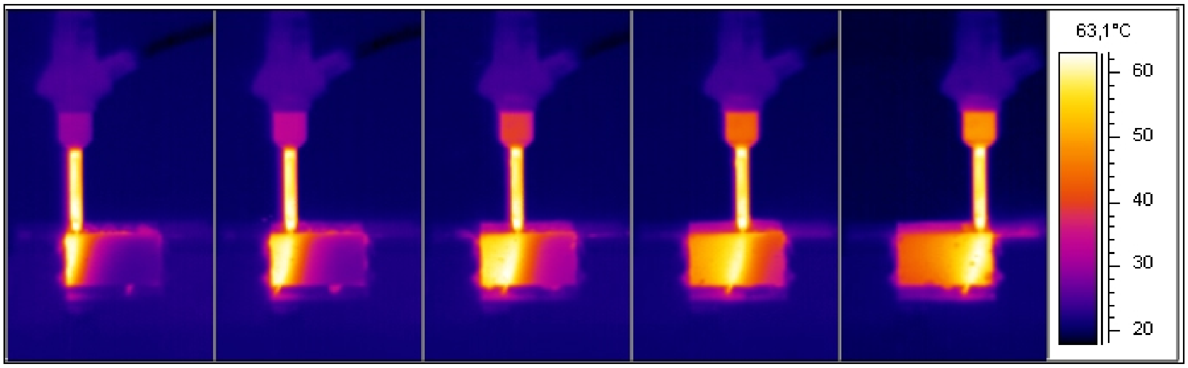

Figure 7. Frames from the recorded sequence of IR thermo grams during AWJ cutting using an 0.25 mm orifice and a focusing nozzle of 0.8 mm from research done by Lebar et al. [9]. Temperatures measured on the focusing nozzle at 300 MPa are similar to the ones measured by thermocouples TC 6-9 in this paper.

Table 1. Volume flow of water at different pressures and orifices.

No.	Pressure	Nozzle setup	Volume flow of water 10^{-5}[m^3/s]
1	100 Mpa	V1F1	1.72
2		V2F1	0.28
5	200 Mpa	V1F1	2.40
6		V2F1	0.38
9	300 Mpa	V1F1	2.90
10		V2F1	0.46

7. NOMENCLATURE

F1	Focusing nozzle with 1,02 mm of diameter.
V1, V2	Orifice with 0.25 mm and 0.10 mm respectively.
V1F1, V2F1	Combination of orifice V1 and V2 respectively, with the focusing nozzle.
R^2	Correlation factor for different water pressures and orifices [ ].