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REVIEW OF THE PRESENT TECHNOLOGICAL ADVANCE IN THE FIELD OF WATER JET CUTTING

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Abstract: *Water jet cutting (WJC) is a relative recent technology that has a high interest due to its results. The main advantage in using this flexible non-conventional technology is that there is no heat-affected zone (HAZ). Another particular use of water jet cutting is when machining heat-sensitive, soft or very hard materials and complex 2D or 3D geometry. Water jet cutting is successfully used in industries like aerospace, automotive, electronics, food, munitions demilitarization, textiles. Present studies in this filed reveal the necessity of developing this technology as micro scale water jet machining. The main goal is to develop new technologies in order to approach alternatives like abrasive water jet machining (AWJM), thermally enhanced abrasive (TEAWJM), cryogenic assisted abrasive (CAJM), ice assisted jet machining (IAJM), submerged jet conditions (SJM). Another important aspect is the simulation of abrasive water jet milling (AWJMi). By means of computer simulation software the method combines calculations of particle-workpiece interactions with water jet characteristics. In order for the water jet technology to be efficient parameters like high pressure and velocity, large array of materials, low energy consumption and high productivity has to be achieved. It is also concluded that this technology allows different processes to be integrated into it, making this a hybrid process.*

Key words: *water jet, hydraulic pressure, machining parameters, flow rate, surface topology, depth of cut.*

1. INTRODUCTION

In the past decades the industry has evolved considerably, leading to new requirements with complex characteristics that call for intricated material machining processes. This need led to the development of new materials and processes that have to be easy to be implemented and sustained. In the end, this evolution requires unconventional processing techniques. One such unconventional technologies is water jet machining. The development of this technology, until recent time, splits it into two major branches: with or without abrasive. This technology was used in its beginning in the mining sector, afterwards being an important breakthrough in the wood industry, more explicit the furniture industry. Furthermore, this technology was used when processing plastics and glass [1].

Given the process nature, the water jet machining is able to deliver a good product quality, flexibility of production and enlargement of economy. The process versatility and adaptability made it ideal for industries like automotive, aerospace or glass. Creating accurate parts from hard-to-cut materials is one the most important aspect of this technology. Also, the productivity of the process is a key factor, so important research and development has to be made in the abrasive segment. Finally this will lead to adaptation to new applications than its current use [2].

The erosion caused by high speed abrasive particle driven by a high-pressure water jet is the mechanism behind the material removal rate (MRR) in AWJM. The plastic deformation that occurs in the cutting zone if machining is performed at high temperatures. This phenomenon leads to the increase in MRR and depth of cut. Taking into consideration this facts, new ways to take advantage of this technology reveal that for hard-to-machine materials can be processed by thermally enhanced machining (TEM). The heat source in this case can be an external one, in order to soften the material. The mechanism behind this process is the following: thermal softening is due to the rise of temperature lead to a decrease in the stress and strain hardening rate flow.

Due to this decrease in flow the yield strength, hardness and strain hardening in the metal sheet reduces. This leads to the fact that the deformation behavior of the hard-to-machine materials changes, therefore it allows plastic deformation to take place. From the machinability point of view, this alterations in properties enables the

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difficult-to-machine materials to be machined easily. Such properties lead to a better material removal tare along with an increase in productivity [3]. The outcome is the reduction in yield strength, strain hardening and hardness while the deformation behavior changes from brittle to ductile. As these phenomena occur difficult-to-machine materials are being processed easily with low power requirements, resulting in the increase of the MRR, thereby the productivity [4].

On the other hand, the process can be adapted for cryogenic machining, that uses cooling liquid at below 0° C. This process leads to the improvement of process performance and surface integrity. It was observed that cryogenic machining lead to increase machinability. Using below 0° C temperature liquids (LN2-liquid nitrogen) has its advantages: enhancing the materials properties, increasing the hardness and providing a superior surface finish. The fatigue live is improved by means of yield strength increase, produced by inducing compressive residual stress. Another key aspect of using liquid nitrogen is that its environmentally safe [5]. A variety of materials were used to investigate the cryogenic water jet machining. Comparing cutting at room temperature and in cryogenic conditions, this last method offers MMR increases. One of the material in which this parameter improves considerably is glass, while the erosion rate for steel increases by a factor of 1.7 [5]. In the case of cutting different polymer materials, it was found that LN2 cryogenic cooling assures that the cutting edge of the inserts, and also on the machined surface are not as susceptible in accumulating deposits of particle embedding. The repeal of the material improves the functional performance of the cut surface [6]. More specific details were revealed when micro-machining of polydimethylsiloxane. The same process parameters were used for machining materials like polytetrafluoroethylene and high carbon steel. For both materials the erosion rate and reduction of particle embedding shown an increase for different angles and low cryogenic temperatures used [8].

The food processing industry has also to gain from this technology as it can process goods faster. A problem thereby is raised when thick pieces have to be processed. This happens when the cross-sections of the processed food have in its composition harder materials, like bone tissue. A problem in this case appears as convention abrasive cannot be used for reasons of hygiene. Many researches in this field shift they attention to acceptable additives such as salt, sugar and starch crystals. The results shown that these additives don't have enough abrasive power when mixed in water. Another step back is that these additives may affect the quality of the meat. In order for this phenomenon not to take place, a viable solution is using ice-particles as a substitute to the classical abrasive. This means that is abrasive reissued remains in the processed food, this will just simply melt [9]. Ice assisted jet machining (IAJM) take its benefits from the water solubility and it's melting characteristics. Ice-particle are softening while they are melting. This will lead to alteration in its abrasiveness strength. High-pressure water leads to a rise in temperature with approximately 80° C at the nozzle outlet [9].

In the study "Technical Possibilities of Noise Reduction in Material Cutting by Abrasive Water-jet" the use of submerged AWJ is taken into consideration as noise generated from the cutting process needs to be reduced. Nevertheless, a part of the kinetic energy in the jet generated during the cutting process is lost [10, 11]. It was noted that when the water jet is submerged, it can cause cavitation erosion on the machined surface. This effect was obtained after two hours from the submerge machining in a stationary slurry [11, 12]. One key aspect of submerged water jet machining is that this method decreases the water jet drag, thereby generating a smaller diameter diffraction along the jet [13]. Taking into consideration that the abrasive water jet machining process is one in which particles of abrasive material fill the environment close to the machine. This will create an atmosphere full of small sharp particles of chips that, when inhaled by the operator, may cause lung micro-perforation, having a serios effect on the long-term human health, especially when materials like aluminum are being processed. Submerging the process eventually lead to a dust free process [14]. Research regarding this issue lead to partial submerging of the process for 2–6 mm. The solution in the tank, where the experiments took place, was liquid glycerin, polymer, and water was adapted for AAJM. The results state that for each one of the above submerged environments 61%, 42%, and 36% dust reduction was recorded. Furthermore, when the nuzzle wear was analyses, no damage was recorded [11, 15]. As particle velocity only reaches between 10÷30 m/s it considered a major deficiency [11].

Comparing to other similar technologies (laser and plasma cutting) the abrasive water cutting method provides a multitude of benefits. D. Krajcarz makes a comparison between these cutting technologies in the study "Comparison Metal Water Jet Cutting with Laser and Plasma Cutting". In this study it is provided a good insight that reveals week and strong point, not only for AWJM. Also, there were thoroughly studied parameters like: economy of the cuts, environmentally friendly treatment, thickness of the cut material, thermal deformation of the cut material, quality of the cut surface, easy programming of the machine. Is was concluded that water jet machining is best suited for cutting of metals [16].

2. INSIGHT IN WATER JET TECHNOLOGIES

Advantages such as: environmentally friendliness, suitability for processing of different metallic or non-metallic materials in different shapes, no burrs are obtained very small loss of material due to the small cutting width; no heat release during processing: the heat generated by bombarding the processed surface with abrasive material is cooled by water; this benefit is very useful in case of processing those materials that lose their chemical and mechanical properties when heat is generated [17].

Also, there are some disadvantages related to the AWJ process as: parts cannot be processed in packet, the high costs of equipment's and consumables (water nozzle, focusing tube, body of cutting head, filters, etc.), large thicknesses cannot be accurately processed since the cut come into a conical shape and burrs occur at the bottom of processed surface, materials that degrade on contact with water cannot be processed. In order to diminish the costs related to the AWJ process, some preoccupations are presented in the scientific literature.

Latest development in technology lead to more effective methods and techniques that help improve water jet cutting. Furthermore, there will be described the following types of water jet machining processes: abrasive water jet machining, thermally enhanced abrasive jet machining, cryogenic assisted abrasive jet machining, ice assisted jet machining and submerged jet machining.

2.1. Abrasive water jet machining (AWJM)

The abrasive water jet machining uses a mixture of high-pressure water jet with abrasive material. This blend takes place into the mixture chamber of the cutting head [18]. The mixture is delivered by a tube which is called a nozzle at which the pressure is relieved. The nozzle is made from sapphire or ruby nozzle has a diameter of approx. 0.08 to 0.5 mm. This very small in diameter size nozzle ultimately expels the water-abrasive mixture with high velocity. The quantity of abrasive material that is fed in the mixing chamber is precisely meters. For water and abrasive to mix the jet creates a partial vacuum. This vacuum actually assure that abrasive is drawn towards the water jet. This is known as the injector principle. Once mixed, the jet stream is refocused by a mixing tube/nozzle.

In the focusing tube two main phenomena take place: the abrasive mixture is accelerated and the jet is focused [19].

The principle of abrasive water jet cutting can be observed in Fig. 1, where: 1 – focusing tube, 2 – case, 3 case protection, 4 – bolt nut, 5 – elastic bushing, 6 – orifice for abrasive material. This cutting method can be used for cutting hard-to-machine materials (stainless steels, various alloys, titanium, aluminum, bronze) with higher thicknesses [19].

2.2. Cryogenic assisted jet machining (CAJM)

As stated, serious development has to be made to this technology in order to achieve flexibility, improvement of process performance and surface integrity. Therefore research in this field lead to the development of low temperature, such as cryogenic water jet machining [5].

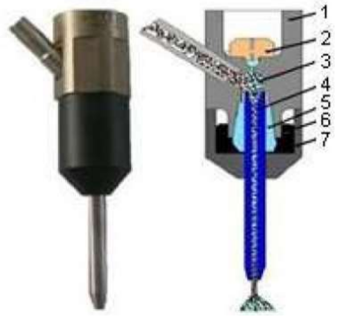

Fig. 1. Schematic diagram of AJM process [19].

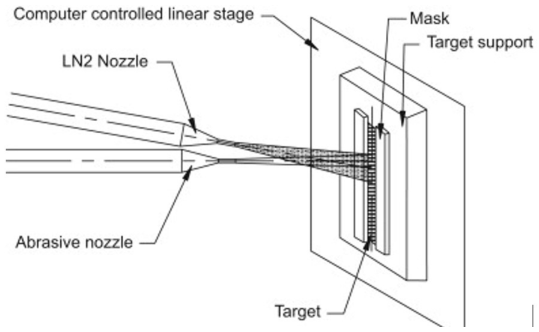

Fig. 2. Schematic of the CAJM process [22].

The main idea behind CAJM is that the material machinability is enhanced at very low temperatures [20].

One of the most successfully analyzed techniques is with liquid nitrogen (LN_2) cooling. The use of liquid nitrogen creates a safe environment for machining exploitation and disposal expansion ration to the surrounding environment [21].

The research work conducted in this field analyses the integrity of the surface integrity in different cryogenic machining processes rather than the CAAWJ cutting process.

In the study "Thermal analysis of cryogenically assisted abrasive jet micromachining of PDMS" [22] dry air at 200 kPa is combined with granular aluminum oxide powder. The size of the grains is roughly 25 µm in diameter that entered the micro-blaster chamber. The mix is then driven through a nozzle. The shape and size of the nozzle were chosen for each type of the performed experiment, as shown in Fig. 2 [22].

The temperature at which most studies were conducted is −192 °C, the temperature of liquid nitrogen (LN_2). In order for this system to work without flows, the liquid nitrogen has to be injected into the abrasive jet after it exits the nozzle. During this process the liquid nitrogen is injected using a separate pressured system. It was taken into consideration also the stand-off distance has to be shorter. As previously described, this leads to a lower velocity of the particle, as the distance on witch they still accelerate to the maximum velocity is up to 20 mm from the nozzle. In this instance a shorter stand-off distance provides lower particle velocity, as particles are still accelerating up to 20 mm from the nozzle [23]. If the stand-off distance is still reduced and the pressure is increased the particles and thus the air mass flux to the surface rise with the increase in collisions between incident and rebounding particles, leading furthermore to greater displacement of incoming particles by the deflected airstream. This phenomenon results in a poor erosion rate [22].

2.3. Ice assisted jet machining (IAJM)

Water jet machining has low productivity in the absence of an abrasive material. Studies were performed in this way and resulted that the presence of crystallized water particles can drastically increase the material removal rate (MRR) [11]. The crystallized water particles together with water jet machining have led to a novel process called ice assisted jet machining (IAJM), which uses grains of ice as the abrasive particles. Generally, ice increases the efficiency of the machining

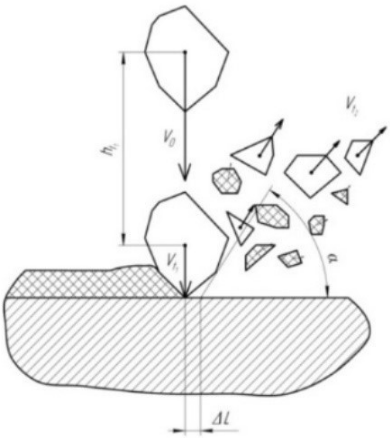

Fig. 3. The scheme of an impact on removable coating of an ice particle and its destruction [27].

by using of pure water jet and AWJM. A standard mixing tube along with dry ice blocks can be used for blending it intro water or air jet [24]. This solution raises furthermore another problem that is the temperature of the system. The temperature has to be controlled so it allows the ice-particles to stay at very low temperature [25]. In order to confirm that hardness and the capacity of ice to remove material efficiently are depended of the jet temperature, the experiments were conducted using a cryogenic wet-ice blasting at around −100 °C [26].

If the material is previewed as a layer upon layer compound, the removal mechanism can be described as the destruction of each layer, systemically. This is caused by a multiphase character that a high speed flow has (water-ice particles) (Fig. 3). Most of the energy from the system was used for accelerating the ice particles. Due to the nature of the process, this cutting technique creates an electric small change/voltage, which varies with its strength that provides mode destruction power. Meanwhile, the ice particles are causing microcracks in the material surface. They concentrate stresses, which enhances cleaning efficiency in general [27].

2.4. Submerged jet machining (SJM)

The submerged jet machining is based on the fact that the flow of the fluid is controlled by back pressure adjustment. This is performed by using a constant inlet pressure in Fig. 4. The properties vary with the adjustment of the total differential pressure [28].

In the study "Erosion characteristics of direct pressurization type underwater abrasive jet" the input parameters used were as fallowing: a pressure of 20 MPa at, with a standoff distances between 20 and 40 mm. This slurry jet machining caused cavitation erosion after two hours from machining [29]. It was noted that this cavitation effect toke place when machining aluminum, using a stand-off distance of 50 mm, for 180 s at a pressure of 240 MPa, water jet diameter of 254 μm and submerged in a slurry solution. Submerging the process leads to different drag resistance applied by the environment (water of air) to the abrasive particles. This drag leads to different effects on the surface topology [30]. One major benefit of this method is that the wear of the nozzle is no longer existent [11].

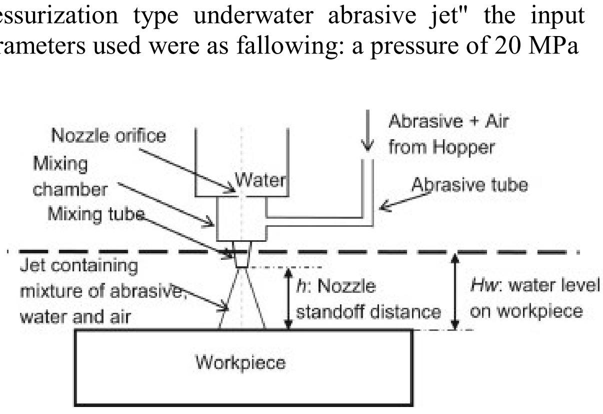

Fig. 4. Schematic of submerged abrasive water jet [31].

2.5. Thermally enhanced abrasive water jet machining (TEAWJM)

There is a tendency to think that inducing a thermal load into a high velocity abrasive water jet will lead to a rapid cooling of the material. This phenomenon take place only when the cutting process take place in catcher tanks, in submerged conditions. Taking this into consideration for the TEAWJM to be effective the machining has to be executed above the water and thus the effect of high temperature on the MRR can be observed. The conditions to warm the workpiece were analyzed in a multitude of studies, but the most important improvement was noted when using oxy acetylene gas welding torch. The reasons behind this selection are the ability to locally heat the material at over 3000 °C, ahead of nozzle. The high temperature assures a relative fast heating time of the sheets. Another key aspect is the ability to regulate the nozzle temperature of the welding torch by adjusting the gas flow. By exact positioning the flow of oxygen and acetylene, a uniform temperature distribution can be achieved. This has to take place at the cutting zone, but without heating the cutting nozzle as seen in Fig. 5 [3].

The mechanism behind this process is that the high temperature effects the cutting zone by reducing the yield strength and material hardness. This leads to a low requirement in cutting energy. Although high temperatures induce residual stresses but even if the material is rapid cooled, the thermo-mechanical changes do not lead to residual stress or crack. However, this defects were observed when mild steel (MS-A36), and the appear as micro-cracks [11].

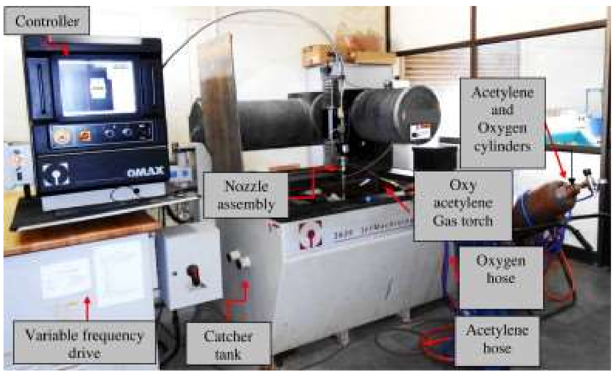

Fig. 5. Schematic of the TEAWJM process [3].

2.6. Material removal simulation for AWJMi

One of the most flexible non-conventional technologies used for process difficult-to-machine materials has proven to be abrasive water jet milling. Present simulation software doesn't offer mathematical models for water jet milling. This means that it cannot calculate the removed material, and thus a modularized material removal simulation for the AWJMi controlled depth machining process has been developed. The logic behind this concept is that the removed material is dependent of the input energy for each unit length from the toolpath that was previously programmed. Problems have to be analyzed in details, as an example may be unwanted deviations of the feed rate that drops at sharp corners [32]. The mechanism of the material removal and flow conditions are essential factors in simulating the solid particle in the fluid stream, thereby linking it to the amount of surface material eroded. As materials are more ductile, the prediction of the removed material has a higher rate of accuracy. The MRR has been shown to be in direct link to the direction and velocity of the eroding particles. Given the large set of numerical data that has to be generated and analyzed the erosion process is very difficult to be described as accurate. The approximation of this simulation has to be improved by correlating with data widely available from the metal cutting sector, like turning or milling. At the other end the brittle materials require more research. This large amount of data generated, that cannot predict exactly what happens during the water jet milling process, is a major step back in predicting the initial crack location and it has to be deduced. This prediction in MRR could not be solved and no other method was found in order to perform an analysis.[33]. In the study "Numerical research on rock breaking performance of water jet based on SPH" [34] the authors analyze the numerical model of rock breaking by water jet.

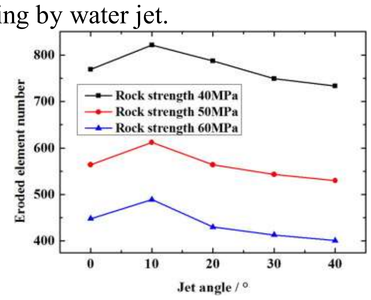

Fig. 6. Rock eroded element number of different jet angles [34].

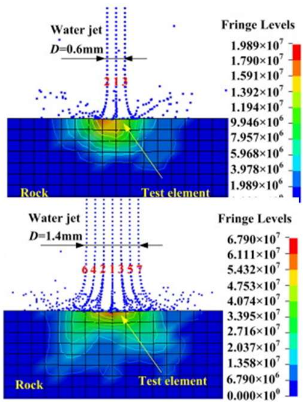

Fig. 7. Effect of jet diameter on rock stress [34].

Different jet angles were simulated and it was concluded that the number of eroded elements increase to a value of 10° afterward a decrease was recorded as shown in Fig. 6. It was also recorded that with the increase of the jet diameter the number of eroded elements increase (Fig. 7) [34].

3. CONCLUSIONS

As a variety of types of water jet cutting processes were analyzed, it can be concluded that it is a promising technique that offers flexibility in manufacturing by means of integrating different technologies into it.

Regardless of the type of process used, the research in this field analyses parameters like surface topography, visual examination, surface morphology, surface texture, surface metallurgy, microstructure examination, XRD peak analysis, residual stress measurements, and microhardness test.

Looking into the analyzed AWJM technical documentation two types of cutting conditions can be highlighted: dynamic and constant parameters. Most of the research in this field regards dynamic process parameters as water pressure, traverse speed and mass flow rate, while the constant parameters are the abrasive mesh size, jewel diameter, nozzle diameter, angle of target, stand-off distance.

While cutting by means of cryogenic jet machining it was observed that this type of heat treatment results in increase in the tensile strength and elastic modulus properties of the material. Therefore the cutting forces increase in this particular type of water jet cutting technique [35].

Ice jet cutting is manly used in present when processing frozen and unfrozen food. One of the major water pressure is needed, while unfrozen processed food remains undamaged [9].

Comparing submerged cutting water jet conditions with unmerged shows that narrower cuts can be made, with the reduction of noise and releasing less abrasive debris to the air [31].

Unlike cryogenic jet cutting the thermally enhanced abrasive water jet process leads to softening the material. This changes the deformation behavior and thus plastic deformation occurs, reducing furthermore the cutting forces and obtaining a higher material removal rate [3].

Software simulation is an essential component of the modern manufacturing process. From simulating the process, itself, by means of material removal, to simulating the manufacturing process, as machine movements computer software allows problems to be solved in early stages. The simulation can calculate the tool path, analyzing interactions between the input parameters and the output ones, highlighting the optimal values [32].

AWJM is a non-conventional technology that allows that complex 2D and 3D shapes to be manufactured. As shown above the flexibility of the process makes it suitable for precise machining such as polishing, drilling, turning and milling. [36].

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REFERENCES

[1] E.R. Herghelegiu, C. Schnakovszky, V. Zichil, *Quality of the Cut Surfaces Processed by AWJC as a Function of the Distance between the Cutting Head and Working Sample*, Applied Mechanics & Materials, 2015.

[2] E. Herghelegiu, M.R., G. Brabie, C. Tampu, *Influence of abrasive material quantity on surface quality generated by abrasive water jet operation,* International Journal of Modern Manufacturing Technologies, 2011.

[3] D. Patel and P. Tandon, *Experimental investigations of thermally enhanced abrasive water jet machining of hard-to-machine metals,* CIRP Journal of Manufacturing Science and Technology, Vol. 10, 2015, pp. 92–101.

[4] S. Sun, M. Brandt, and M.S. Dargusch, *Thermally enhanced machining of hard-to-machine materials—A review,* International Journal of Machine Tools and Manufacture, Vol. 50, No. 8, 2010, pp. 663–680.

[5] N. Yuvaraj and M.P. Kumar, *Cutting of aluminium alloy with abrasive water jet and cryogenic assisted abrasive water jet: A comparative study of the surface integrity approach.* Wear, Vol. 362-363, 2016, p. 18–32.

[6] H. Getu, J.K. Spelt, and M. Papini, *Cryogenically assisted abrasive jet micromachining of polymers,* Journal of Micromechanics and Microengineering, Vol. 18, No. 11, 2008, p. 115010.

[7] A.G. Gradeen, A.G., J.K. Spelt, and M. Papini, *Cryogenic abrasive jet machining of polydimethylsiloxane at different temperatures.* Wear, Vol. 274-275, 2012, pp. 335–344.

[8] A.G. Gradeen, M. Papini, and J.K. Spelt, *The effect of temperature on the cryogenic abrasive jet micro-machining of polytetrafluoroethylene, high carbon steel and polydimethylsiloxane.* Wear, Vol. 317, No.1, 2014, pp. 170–178.

[9] J.A. McGeough, *Cutting of Food Products by Ice-particles in a Water-jet.* Procedia CIRP, Vol. 42, 2016, p. 863–865.

[10] A. Radvanská, T.E., Željko Ivandić, Sergej Hloch, Jan Valiček, Jana Mullerova, *Technical Possibilities of Noise Reduction in Material Cutting by Abrasive Water-jet.* 2009.

[11] R. Melentiev and F. Fang, *Recent advances and challenges of abrasive jet machining.* CIRP Journal of Manufacturing Science and Technology, Vol. 22, 2018, pp. 1–20.

[12] Y. Murakami and H. Ishii, *Fischer Indolization and Its Related Compounds. XVI. Vilsmeier-Haack Reaction of N-Methyl-1, 2, 3, 4-tetrahydrocarbazole Derivatives.* CHEMICAL & PHARMACEUTICAL BULLETIN, Vol. 29, No. 3, 1981, pp. 711–719.

[13] N. Haghbin, J.K. Spelt, and M. Papini, *Abrasive waterjet micro-machining of channels in metals: Model to predict high aspect-ratio channel profiles for submerged and unsubmerged machining.* Journal of Materials Processing Technology, Vol. 222, 2015, pp. 399–409.

[14] D. Krewski et al., *Human Health Risk Assessment for Aluminium, Aluminium Oxide, and Aluminium Hydroxide.* Journal of Toxicology and Environmental Health, Part B, Vol 10 (supl), 2007, pp. 1–269.

[15] R.H.M. Jafar et al., *Dust reduction in abrasive jet micro-machining using liquid films.* Powder Technology, Vol. 301, 2016, pp. 1270–1274.

[16] D. Krajcarz, *Comparison Metal Water Jet Cutting with Laser and Plasma Cutting.* Procedia Engineering, Vol. 69, 2014, pp. 838–843.

[17] C. Schnakovszky, M.C. Radu, V. Zichil, *Effects of reusing abrasive material in abrasive water jet cutting on the quality of processed surfaces and environment*, 2014.

[18] M. Radovanović, *Precision Cutting By Abrasive Waterjet.* 2004.

[19] E. Herghelegiu, C. Radu, C. Schnakovszky, I. Cristea, *Influence of the Distance between the Cutting Head and Working Sample on the Geometric Precision in Water Jet Abrasive Cutting Process,* Applied Mechanics and Materials, Vol. 371, 2013, pp. 240–244).

[20] S. Ravi and M.P. Kumar, *Experimental Investigation of Cryogenic Cooling in Milling of AISI D3 Tool Steel.* Materials and Manufacturing Processes, Vol. 27, No. 10, pp. 1017–1021.

[21] R. Natasha, J.G. Che Haron, J. Syarif, *The Effect of Cryogenic Application on Surface Integrity in Manufacturing Process: A Review,* Journal of Applied Sciences Research, Vol. 8. No. 10, 2012, pp. 4880–4890.

[22] H. Getu, J.K. Spelt, and M. Papini, *Thermal analysis of cryogenically assisted abrasive jet micromachining of PDMS,* International Journal of Machine Tools and Manufacture, No. 9, 2011, pp. 721–730.

[23] A.N.J. Stevenson and I.M. Hutchings, *The influence of nozzle length on the divergence of the erodent particle stream in a gas-blast erosion rig.* Wear, Vol. 189, No. 1, 1995, pp. 66–69.

[24] V. Máša and P. Kuba, *Efficient use of compressed air for dry ice blasting.* Journal of Cleaner Production, Vol. 111, 2016, pp. 76–84.

[25] M. Jerman et al., *Measuring the Water Temperature Changes in Ice Abrasive Water Jet Prototype.* Procedia Engineering, Vol. 149, 2016, pp. 163-168.

[26] B. Karpuschewski et al., *Cryogenic wet-ice blasting—Process conditions and possibilities,* CIRP Annals, Vol. 62. No. 1, 2013, pp. 319–322.

[27] M. Burnashov, A. Prezhbilov, and E. Stepanova, *Modelling of destructive ability of water-ice-jet while machine processing of machine elements,* MATEC Web Conf., Vol. 129, 2017, p. 01014.

[28] T. Qiu et al., *Investigation on effects of back pressure on submerged jet flow from short cylindrical orifice filled with diesel fuel,* Energy, Vol. 162, 2018, pp. 964–976.

[29] S. Shimizu, *Erosion characteristics of direct pressurization type underwater abrasive jet,* Vol. 59, No. 566, pp. 2964–2968.

[30] J. Madadnia et al., *A Study of Cavitation Induced Surface Erosion in Abrasive Waterjet Cutting Systems.* Advanced Materials Research, Vol. 53-54, 2008, pp. 357–362.

[31] N. Haghbin, J.K. Spelt, and M. Papini, *Abrasive waterjet micro-machining of channels in metals: Comparison between machining in air and submerged in water.* International Journal of Machine Tools and Manufacture, Vol, 88, 2015, pp. 108–117.

[32] F. Klocke et al., *Material Removal Simulation for Abrasive Water Jet Milling.* Procedia CIRP, Vol/ 68, 2018, pp. 541–546.

[33] I. Finnie, *Erosion of surfaces by solid particles,* Wear, Vol. 3, No. 2, 1960, pp. 87–103.

[34] X. Liu, S. Liu, and H. Ji, *Numerical research on rock breaking performance of water jet based on SPH.* Powder Technology, Vol. 286, 2015, pp. 181–192.

[35] S. Morkavuk et al., *Cryogenic machining of carbon fiber reinforced plastic (CFRP) composites and the effects of cryogenic treatment on tensile properties: A comparative study*, Composites Part B: Engineering, Vol. 147, 2018, pp. 1–11.

[36] M.M. Korat and G.D. Acharya, *A Review on Current Research and Development in Abrasive Waterjet Machining,* 2014.