EFFECT OF WATER JET PRESSURE IN ABRASIVE WATER JET MACHINING PROCESS OF VARIOUS MATERIAL – A REVIEW

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ABSTRACT:

Abrasive water jet machining (AWJM) is a modern manufacturing technology in the category of Non-conventional machining process, which uses a high pressure water jet with fine abrasive particles. This mixture has been used to machine the hard materials by means of erosion technique. The focus of this review work is to provide existing research details related to the effect of water jet pressure on Material Removal Rate and Surface Roughness with the machining of various base materials in the AWJM process. The period of the past 10 years was considered for this review.

KEYWORDS: *Abrasive water jet machining; water jet pressure; Material Removal Rate; Surface roughness.*

1. INTRODUCTION:

Abrasive water jet machining (AWJM) is one of the modern machining processes and it is an extended version of the water jet machining process. It is widely used in civil and mechanical related engineering applications [1, 2]. The machining process can be categorized in two ways, which are (i) machining with traditional or conventional technique and (ii) machining with modern machining or non-conventional technique [3]. The material removal process is basically done by the machine and cutting tools to produce the required shape of the work material. The conventional machining processes is having limitations in machining the hard materials like various alloys, titanium, nickel, granite, marble, tiles, glass, carbon fiber-reinforced plastic (CFRP) composites, etc. [2, 4].

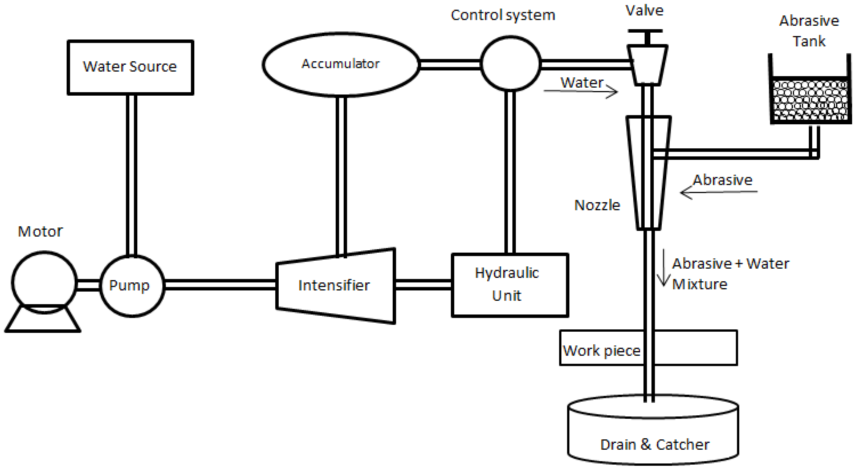

Figure 1: Schematic of AWJM unit

Successful machining of these materials through the modern machining processes has added substantial support to industrial growth and it improves the dimensional quality of work materials. The different modern machining processes usually used in the industries are Abrasive Water Jet Machining (AWJM), Electric Discharge Machining (EDM), Electrochemical Machining (ECM), Ultrasonic Machining (USM) etc.,[5, 6]. From which, AWJM owning unique merits like a wide range of machining operations like, low/minimum heat distortion, minimal tool wear, higher cutting flexibility, no thermal damages, no microstructural changes zones and internal stresses. In addition, AWJM can easily penetrate through thicker cross-section by involving minimal stress and cutting force [7, 8]. The components of AWJM are shown in figure-1. It consists of a hydraulic pump, intensifier, hydraulic accumulator, control valve, mixing chamber and nozzle.

The hydraulic pump is used to pump the water from the reservoir to the AWJM unit through an intensifier. It delivers at a low pressure of about 5 bar to the intensifier, a booster is also used serially which increases the initial pressure from 5 bar to 11 bar before delivering it to the intensifier. The intensifier is used to boost the pressure from 11bar to very high pressure of 300 to 400 Mpa. Basically, the accumulator eliminates pressure variation/fluctuation/water hammer in the water circuit of the machining process and also compensates the fluid when the high pressure energy is required in the line. The control valve ensures the required pressure and nozzle converts the pressure (energy) of water into high velocity beam of water jet (kinetic energy) with direction. The gravity-fed abrasive particles and high pressure water are mixed in the vacuum chamber of the nozzle. The sectional view of the mixing chamber and nozzle unit is shown in figure-2.

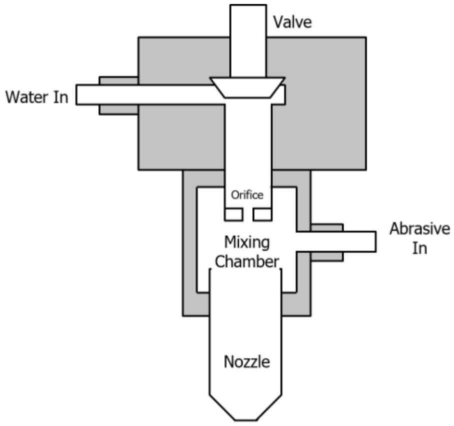

Figure 2: Sectional view of mixing chamber and Nozzle unit

Drain and catcher system facilitates to separate the metal particle and other unwanted particles from the water and re-circulate it to the reservoir for further use after proper filtration. The common parameters used in the machining technique are given in Table.1. AWJM is a very useful machining technique that can be suitable instead of many other machining techniques; however, it has few constraints in machining. The jet may lead to scattering when the thickness of the base material is too high, which results in a rough wave pattern on the machined surface. Also, dimensional inaccuracy occurs when the abrasive jet comes out with a different angle than it enters. Due to embedding of abrasives during machining is known to have an unfavorable effect on component fatigue life [9]. In the past two decades, there has been an exponential rise in the research papers that discuss AWJM [5] in different fields of applications. The results of the machining process are commonly measured by several output responses, such as Material Removal Rate (MRR), Surface Roughness (SR), Kerf geometry (K) with various operating (input) parameters like Water jet Pressure (P_{wj}), Traverse Speed (S_T), Stand-Off Distance (SOD), Abrasive size, Material Flow rate (F_m), etc.

Table 1: Common Parameters in AWJM

S. No	Parameter	Range
1	Orifice diameter	0.1 mm to 0.3 mm
2	Nozzle diameter	0.8 mm to 2.4 mm
3	Pressure range	250 MPa to 400 MPa
4	Abrasive size	125 mesh to 60 mesh
5	Abrasive flow rate	0.1 Kg/min to 1.0 Kg/min
6	Stand-off distance	1 mm to 2 mm

7	Nozzle tilt angle	60^o to 90^o
8	Traverse Speed	100 mm/min to 5 m/min
9	Depth of Cut	1 mm to 250 mm

2. METHODS AND MATERIALS:

The materials which are difficult to machine by conventional machining are chosen as base materials in the AWJM process. Also, it is effective for the materials which should not be affected by thermal distortion and internal stresses which are machined under the AWJM process. The AWJ process is commonly engaged by the industry, academicians and researchers are Machining, Cutting, Drilling, Milling and De-scaling. Even though the process is variety, the basic operation and functions of the set-ups are the same. The method varies based on the use of the abrasive water jet with controlled parameters. Such as water jet pressure, orifice diameter, abrasive flow rate, abrasive material size, nozzle speed, stand-off distance, nozzle impingement angle, etc. Further, the materials which are hard to machine by conventional methods are range from Titanium, Marble, Ceramics, Glass, Aluminium alloy with different grades, Carbon fiber reinforced polymer (CFRP) composites and different grades of Steels. This section describes the various base materials used by the researchers for the study of influences of the machining parameters and also shown in Table 2.

Table 2: Various operations, Materials and Parameters of AWJ

Author's	**AWJ-Method**	**WaterJet Pressure**	**Base Material**	**Thickness**	**MRR**	**Ra**
Niranjan et al. [24]	Cutting	300 Mpa	AZ91/Al2O3 nano-composites	70mm	max	5.64 µm
Nandakumar et al. [25]	Cutting	350 Mpa	Hybrid aluminium 7075 metal matrix composites	15 mm	max	3.1 µm
Thakur et al. [26]	Cutting	304 Mpa	Hybrid carbon/glass composite	6 mm	max	1.32 µm
Arghya Bagchi et al. [27]	Cutting	45ksi	Nimonic C263 super alloy	8.2 mm	11 mm3/s	2.2 µm
prabhuswamy & Srinivas [28]	Cutting	300 Mpa	aluminium alloy (Al 6061) & Matrix	70 mm	max	4.33 µm
pon selvan et al. [10]	Cutting	400 Mpa	aluminium	60 mm	max	min
Rui guo et al. [29]	De-scaling	70 Mpa	Q235 steel	x	max	1.80 µm
Nguyen & wang [30]	Drilling	25 Mpa	Amorphous soda-lime glass sheet with 4H -Sic film coating	5 mm	max	14 µm
Potom B et al. [31]	Drilling	2500 bar	CFRP composites	5 mm	6.7 g/min	Min

Suresh R et al. [32]	Drilling	6 bar	Borosilicate Glass and GFRP Composites	3.5 mm	0.6209 gm/min	Min
Siva Prasad & Chaitanya [17]	Drilling	225 Mpa	CFRP composites	4 mm	1.819 gm	3.48 µm
Patel et al. [33]	Machining	150 Mpa	Polimer Matrix composites (PMC)	6 mm	344.3 mm3/min	0.273 µm
Adam khan & K Gupta [34]	Machining	240 Mpa	EN24 steel	20 mm	500 mm3/min	2 µm
Srinivasan et al. [35]	Machining	280 Mpa	AZ91 magnesium alloy	x	max	4.29 µm
Pahuja R & Ramulu [36]	Machining	275 Mpa	Titanium Alloy Ti-6Al-4V & CFRP stacks	15.5 mm	max	11.6 µm
Ketan Verma et al. [37]	Machining	250 Mpa	AA2014 aluminium alloy	X	max	Min
Senthilkumar et al. [38]	Machining	350 Mpa	Al 4032 Hybrid Metal Matrix Composites (HMMC)	x	max	Min
Ramakrishnan et al. [15]	Machining	200 Mpa	Titanium Alloy Ti-6Al-4V	10 mm	max	2.68 µm
pon selvan et al. [39]	Machining	380 Mpa	mild steel (carbon from 0.06% to 0.26%)	70 mm	max	3.2 µm
Jesthi et al. [16]	Machining	5 Mpa	CFRP composites	3 mm	$4 x10^{-3}$ g/s	1.5 µm
Vivek Bhandarkar et al. [21]	Machining	35 Mpa	Nickel based superalloys	10 mm	max	Min
Shanmugam et al. [40]	Machining	192 Mpa	Hybrid aluminium 7075 metal matrix composites	10 mm	max	1.78 µm
Gnanavelbabu et al. [41]	Machining	275 Mpa	aluminium alloy (Al 6061) & B_4C Matrix	3 mm	max	Min
El-Hofy et al [42]	Machining	350 Mpa	Multidirectional CFRP Laminates	10.4 mm	max	Min
Shahu & maity [13]	Machining	320 Mpa	aluminium alloy (Al 6061) & Matrix	x	max	Min
Gnanavelbabu & Saravanan [43]	Machining	275 Mpa	Titanium Alloy Ti-6Al-4V	5 mm	max	2.1 µm
B Tank & S Kumar [44]	Machining	240 Mpa	carbon fibre vinyl ester composite	20 mm	max	Min
Gnanavelbabu et al. [45]	Machining	275 Mpa	aluminium alloy (Al 6061) & Matrix	10 mm	max	3.313 µm
Tanmay Tiwari et al. [19]	Machining	38 Mpa	alumina ceramic	18 mm	53.05 mm3/min	8.125 µm
Senthil Kumar et al [18]	Machining	140 Mpa	Marble	6 mm	8.394 mm3/min	2.276 µm
Saurabh S et al. [20]	Machining	45ksi	alumina ceramic	18 mm	62.02 mm3/min	5.01 µm
Murugan et al. [46]	Machining	34 Mpa	mild steel, aluminium alloy 6061 and plastics Delrin	x	max	2.5 µm
Gnanavelbabu et al. [14]	Machining	275 Mpa	Titanium Alloy Ti-6Al-4V	5 mm	345.8 mm3/min	2.132 µm
Gnanavelbabu et al. [12]	Machining	275 Mpa	aluminium alloy (Al 6061) & Matrix	10 mm	14.99 mm3/min	3.012 µm
Arun Raj et al. [22]	Machining	43000 psi	Nickel based superalloys	10 mm	17.25mm3/min	1.16 µm
Jayakumar [47]	Machini	225	Kenaf/E-glass fiber - reinforced hybrid polymer	x	max	3.254

	ng	Mpa	composite			µm
Uthayakumar et al. [23]	Machining	280 Mpa	Nickel based superalloys	10 mm	150 mm3/min	3.55 µm
Sasiumar et al. [48]	Machining	280 Mpa	Hybrid aluminium 7075 metal matrix composites	10 mm	max	2.5 µm
Babu & Muthukrishnan [49]	Machining	399 Mpa	Brass 360	x	max	5.19 µm
Babu & Nambi [50]	Machining	300 Mpa	AA 6351 alloy	x	max	2.6 µm
Srinivas & Ramesh Babu [51]	Machining	300 Mpa	Al-SiCp MMCs	5 mm	max	5 µm
Azlan et al. [52]	Machining	125 Mpa	Hybrid aluminium 7075 metal matrix composites	x	max	1.524 µm
Mustafa et al. [53]	Machining	3600 bar	Nickel based superalloys	4.76 mm	max	Min
Mardi K et al. [54]	Machining	400 Mpa	Mg-Based Nanocomposite	8 mm	max	3.6 µm
Gopichand & Sreenivasarao [55]	Milling	170 Mpa	Hastelloy C-276	6 mm	336 mm3/min	2.32 µm

The main use of Aluminum alloys [10-13] is in aviation and automotive fields for their lightweight, better corrosion resistance, high strength-to-weight proportion and relatively low cost. The chemical composition of the 7075 Al alloy matrix was (wt%): 1.6 Cu, 2.6 Mg, 0.11Si, 0.21 Cr, 5.4 Zn, and balance Al. The stir casting method was generally adopted to fabricate the aluminum hybrid composite. Titanium (Ti-6Al-4V) alloy [14, 15] is a high quality, great corrosion obstruction, light-weight and imperviousness to fire material because of which it is generally applied in elite car parts, marine, airship industries and medical gadget applications. It is exceptionally hard to machine such high hardness alloys utilizing by ordinary machining. Carbon fiber-reinforced polymer (CFRP) composites [16, 17] have been well noticeable in basic and non-stack bearing applications, remarkably for elite aviation parts and in addition low-end consumers goods. Composite materials are characterized as a mix of at least two synergic micro-constituents, which contrast in physical shape or synthetic synthesis. The structure of composite materials comprises of two segments, in particular matrix and reinforcement, Jute texture was utilized as a fortification in polymer framework.

Marble [18] is a stone resultant from the variability of sedimentary carbonate rocks which causes variable recrystallization of the original carbonate mineral grains. The ensuing marble rock is naturally made out of an interlocking mosaic of carbonate stones. Marble has different applications for building and upgrading purposes. Its properties are hardness-4MC, density 2.65kg/m^3, compressive force 1800 to 2100 kg/cm^2. Ceramics [19, 20]is a leading engineering oxide mud material and has wide applications. Al_2O_3 ceramics production is depicted by high quality and hardness, low thickness, and high temperature robustness and its principle compound structures are SiO_2-0.03%, Al_2O_3-99.7%, Fe_2O_3-0.028% and significant properties like density-32.26%, shear modulus-127GPa, tensile force-0.32GPa. Nickel-based super alloys are Inconel-617, 625 & 718 [21-23] which are nickel-chromium-cobalt molybdenum blend which is hard to machine material used for various high temperature segments like headers, pipes and turbine sharp edges in ultra-supercritical power plants.

3. INFLUENCES OF PROCESS PARAMETERS:

AWJM process execution relies upon different process parameters/factors, the effectiveness and nature of the manufacturing process impacts by various dominant variables, including energy factors, geometry elements and material factors. The energy factors incorporate water pressure, abrasive feed rate, and traverse speed. Geometry elements principally are the standoff distance between the centering tube tip and the objective work-piece surface. Material factors are for the most part about the physical properties of the target work-piece and abrasive particles. Jet pressure will influence the speed of the abrasive flow through a nozzle that the kinetic strength. The surface roughness development can be accomplished with increment in jet pressure [54]. Traverse speed implies that the speed of the nozzle movement for machining the object longitudinally, which will be chosen by the activity necessity. On the off chance that speed is high, the abrasive penetration will be less on the object and another way that if the speed is low, the depth of cut will be more with a wider gap. Stand-off distance (SOD) is the gap between the object surfaces to the nozzle tip. In the event that the SOD is low, the surface finish and MRR will have esteem decrease and then again, higher SOD will develop the kerf geometry due to divergence. Abrasive particle size will be seen on the impression on the cut surface; higher grain measure is the impression of higher abrasive particle size and wise versa. Abrasive flow rate is the one, the amount of the abrasive particles fed into the water jet in a specific time. Expanding the flow rate will decrease the particle velocity in other mean kinetic energy.

The ideal choice of process parameters assumes a significant role to promise the quality of the product, to minimize the machining expenditure and to enhance the effectiveness of any machining process. This paper illustrates the advancement normal for process parameters in the current machining process known as the abrasive water jet machining process. In the past literature, most of the researchers have demonstrated their interest in AWJM considering the machining parameters, for example, water pressure, abrasive flow rate, nozzle traverse speed, stand-off distance and abrasive grain size into thought. The depth of cut, MRR, surface roughness and Kerf geometry have been considered as median as they are easy to be measured and tracked.

4. EFFECTS OF WATER JET PRESSURE:

This is an important process parameter in the AWJ machining process. The kinetic energy of the AWJ depends on the Pressure range of water. Water jet pressure is directly proportional to the penetration depth and the material removal rate. It has an influence on the distribution of water as well as abrasive particles in the jet. It is frequently denoted by MPa or bar or psi. High-pressure range of max 600Mpa water is fed through a small orifice and abrasives particles were mixed according to the requirements in order to erode the base material without disturbing its mechanical properties. This section briefs the impact of water jet pressure on the base material with the responses of MRR and Ra, which is reflected in Table.2 and Figure.3 shown as an example of some base materials.

The machining of Aluminium alloy in different grades was experimented by Nandakumar et al., (2020)[25] for Al 7075, Prabhuswamy & Srinivas (2018)[28] for Al 6061, Ketan Verma et al. (2019)[37] for AA2014 and Babu & Nambi (2014)[50] for AA 6351 with the work material thickness of 10mm to 70mm correspondingly to predict the impact of water jet pressure on the Surface roughness (Ra). In all the results indicating that surface roughness values decrease with an increase in water pressure. Aluminum alloy 7075 material is utilized in the Design of experiments and statistical demonstrating procedures are engaged by Ahmed TM et al. [7] to build up a connection between the control factors and yield reactions. Response Surface Method (RSM) is utilized for Ra modeling. The outcomes demonstrated that an enhancement of the Ra can be accomplished by raising the water pressure with other parameters. They concluded from their exploration that, the best surface roughness value is (3.628 mm) was accomplished at traverse speed (125.676 mm/min), water pressure (140.54 MPa) and standoff distance (1.405 mm). On the other hand, machining of aluminium composites was also examined with optimization techniques by Senthilkumar et al. (2019)[38], Shanmugam et al. (2019)[40], Sasiumar et al. (2019)[48] and several other researchers to improve the surface roughness to the possible extent and in total, they could conclude that the contributions of water jet pressure for 100% alloy are 33.7% and for composites, the contributions of water jet pressure in the surface finish are 50% along with other controlling parameters.

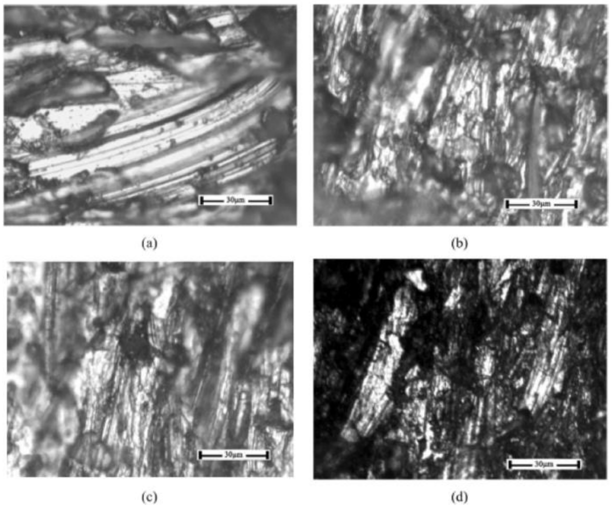

Figure.3: Microstructure of different materials machined by AWJ
(a) 6061 aluminium alloy (b) high strength low alloy structural steel
(c) Q345, high-strength low alloy structural steel, (d) CrWMn, cold work mold steel [56]

Pahuja R & Ramulu (2019)[36], Ramakrishnan et al. (2019)[15] and Gnanavelbabu & Saravanan (2018)[43] were taken the material of Titanium Alloy Ti-6Al-4V to a machine with AWJM process and their results depicted that the minimum surface roughness values which are highly influenced by the waterjet pressure and stand-off distance, also water jet pressure is the most significant factor in reducing surface roughness (Ra) compared to other operating factors. Mardi Kumari et al. (2018)[54] revealed that the pressure of the water jet impacts the general execution of the abrasive water jet slicing system through operational and phenomenological impacts. The impact of water pressure in the surface quality of Mg-based nano-composite was explored. The outcomes demonstrate that the surface quality is better at higher pressure. Say, the values are around 3.4 µm when the water pressure is 400 MPa whereas, at 100 MPa pressure, it varies between 5 and 6 µm and also noticed that insufficient material removal due to low kinetic energy of the abrasive particles. Respectively Qiang et al. (2018)[2] team proposed a multi-objective cuckoo search algorithm (MOCS) for inspecting the optimization of energy utilization and wear rate while applying rapid water jet machining process. On their examination, while the water pressure is more than 350 MPa, the energy input was to a great degree in AWJ. The ideal output energy resulted in around 9.2% higher than the underlying model.

Uthayakumar et al. (2016)[23] examined the machinability of nickel-based super composites by the AWJM process. The impact of machining parameters is assessed based on MRR. The water jet pressure is the most affecting factor identified with the material removal morphology and surface finish. At high jet pressure with moderate traverse speed, machining of super composites can give great surface finish, which shows that the MRR is 150 mm3/min of maximum with a jet pressure of 260 MPa. Guo R et al. (2020)[29] investigated the de-scaling effect by increasing the pressure from 30 MPa to 70 MPa and found that the surface roughness increased from 2.6µm to 1.8µm. Thakur et al. (2019)[26] experimentally tested the cutting of Hybrid carbon/glass composite and they could be revealed from their study that optimum machining condition for surface roughness of was achieved at high jet pressure (304 MPa) and low standoff distance (1 mm) and traverse rate (72 mm/min). Meanwhile, Adam khan & K Gupta (2020)[34] could able predict with their experiment was, for a better result in the MRR is jet pressure followed in the range of 35-36% and 26-37% for surface roughness on the machining of EN24 grade steel plate of 20mm thickness.

Multi-objective optimization of responses was done using desirability approach by Tiwari et al. (2018)[19] for machining of 18mm thick alumina ceramic plate, which gave optimal values of material removal rate as 53.051 mm3/min and surface roughness as 8.125 µm with input parameter level set at 38MPa of water pressure and Saurabh S et al. (2018)[20] concluded that with an increase in pressure, MRR and SR increases with optimum value of MRR and surface roughness were measured as 62.02mm3/sec, 5.01µm. Gopichand & Sreenivasarao (2019)[55] investigated the first time using the operation AWJ milling to machine Hastelloy C-276 Ni-Mo material in detail. They identified using the DFA tool, the optimal processing conditions of 190MPa water jet pressure and the same is validated by experimental the optimal conditions gave values of 170 Mpa for maximum MRR and minimum SR. Babu & Muthukrishnan (2014)[49] were conducted an investigation on AWJM of brass 360 material, their results with the optimal pressure of 399 Mpa could obtain the average roughness value of 5.19 µm.

The study of estimating the optimal process parameter while machining the Marble was conducted by Senthil Kumar et al. (2018)[18] by the optimization tool, Taguchi weightage method and Grey Relational Analysis. In general, both the analysis reveals that material removal rate (MRR), surface roughness (Ra) and kerf Angle (Ka) is significantly affected by Water jet pressure. From comparison Grey relational method gives the best optimum result, Material Removal Rate (MRR) 8.3939; Surface Roughness (Ra) 2.2761µm with the impact of high water jet pressure. In total, all the researchers conclusion indicating that the increase in water jet pressure affecting positively the material removal rate, depth of penetration, cutting efficiency and a decrease in the Surface roughness value, kerf taper angle. The occurrence of an increase in water jet pressure resulted in the transfer of more kinetic energy to the abrasive particles which strike over the target material surface.

5. CONCLUSIONS:

Through a detailed review of research articles, it has been observed that the controlling process parameters like water jet pressure, abrasive size and flow rate, stand-off distance and traverse speed will decide the MRR, Machining time and surface quality. This review article considered only the water jet pressure and its impact on the MRR and Ra. The researchers have discovered that an enhancement of the surface roughness can be accomplished by raising the water pressure at low traverse speed and increased abrasive flow rate. It was evident from the narrow survey; the maximum of Material removal rate (MRR) and lowest surface roughness (Ra) were produced basically by the water jet pressure and followed by other parameters.

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