Nozzle Wear Parameter in Water jet machining

The Review

[1]Saurabh Verma, [2]Dr.S.K.Moulick, [3] Mr.Santosh Kumar Mishra

[1] ME Student, [2] Professor Mechanical Engineering, [3]AP Mechanical Engineering
[1,2,3]Mechanical Engineering, BIT Durg - Durg, India
[1] saurabhp1829@gmail.com, [3] san810@gmail.com

***Abstract*— Abrasive waterjet (AWJ) machining process utilized increasingly in industrial applications. It is a non-traditional machining process and involves complex mechanics. A nozzle is required to perform abrasive waterjet machining for material removal with the help of very high velocity of waterjet. The main problem of AWJ machining process is nozzle wear during the process. The wear depends on various parameters such as water jet characteristics, nozzle geometry, etc. The nozzle wear is not fully understood experimentally. Also the uncontrolled nozzle wear can affect the effectiveness and surface finish obtained through the AJM process. In this paper we propose to investigate and analyze in detail the nozzle wear (using ANSYS FLUENT). A comprehensive literature review for the proposed work is also being described. This analysis can be highly helpful for understanding nozzle wear during the AJM process.**

***Keywords*- Abrasive waterjet (AWJ) machining, nozzle geometry, nozzle wear, fluid flow, MRR**

I. Introduction

Abrasive waterjet (AWJ) machining process is non-conventional machining process, which has been used in industrial applications. A focused stream of abrasive particles carried by high pressure water is made to impinge on the work material is removed by erosion by high velocity Abrasive particles. In abrasive waterjet machining process pure water (tap water) is used and for abrasive particles like sand (SiO_2), glass beads, Aluminum oxide, silicon carbide is generally used. Two types of nozzles generally used for average material removal, tungsten carbide nozzle have a useful life of 12 to 13 hr. and sapphire nozzles have a useful life of 3hr. The inventions of the Abrasive waterjet in 1980 and 1983 the first commercial system with Abrasive entrainment in jet become available.

<u>List of AWJM systems:</u>

- AWJM-entrained-three phase-abrasive, water and air
- AWJM-suspended-two phase-water and air

<u>Advantage:</u>

- Extremely fast setup and programming
- No start hole required
- There is only one tool and less vibration
- Environmentally friendly and low capital cost
- No heat generated in work piece

<u>Disadvantage:</u>

- Low material removal rate
- Abrasive powder cannot reused
- Tapper is also problem
- Due to stay cutting accuracy is affected

<u>Application:</u>

- Cutting soft material and drilling
- Turning and paint removal
- Pocket milling and cutting
- Textile, lather industry and cleaning
- Penning and surgery

II.LITERATURE REVIEW

1.Experimental studies on AWJ machining

M. Hashish et al. (1994) [1] experimentally investigated observations of wear of abrasive-waterjet nozzle materials. The mixing tube, which is where the abrasive are mixed, accelerated, and focused with the high-pressure waterjet, is the component in the abrasive waterjet nozzle that receives the greatest wear. Two general patterns of wear were observed, divergent wear pattern occurs when soft mixing tube materials or relatively hard abrasives were used. Convergent were pattern occur otherwise. This wear will affect the efficiency of momentum transfer between the water and the abrasives and exit diameter wear in particular has a effect on the width of the cut for machining metal. Hashish indicated the complexity of the process, which involves a high-velocity, three-phase flow.

The Accelerated wear test were performed in this study and in this study less wear resistance mixing tube made from steel or by using abrasive that are harden then garnet, such as aluminum oxide. The objective was to use the abrasive-waterjet to find a correlation between the candidate nozzle material's wear performance and its machinability. And some factor influence nozzle wear were discussed here like mixing tube material, length, abrasive particle size, waterjet diameter and to provide identification of desired nozzle characteristics. The main objective of this test was to determine the critical ratio of particles diameters to tube diameter at which the wear rate stabilizes and become very slow.

Effect of particle size:

Below fig.1 showed the four different garnet abrasive sizes. For all abrasive sizes, the final exit diameter of the tube was about the same. The data becomes very slow was independent of particle size and suggest that the stabilizing exit diameter is not a function of particle size. In this test tool steel (R_c=62) mixing tube exit diameter wear- P = 207MPa, d_n=0.457 mm, d_m=2.3mm, l_m=76mm, m_a=7.5 g/s garnet abrasive, mesh 60 (dp=406µ).

Effect of Waterjet Size

The ratio of the mixing tube exit diameter to the waterjet orifice diameter was listed on graph for three different waterjet diameters. This ratio appears to be a function of the waterjet diameter and decrease with increasing waterjet diameters from fig.2.

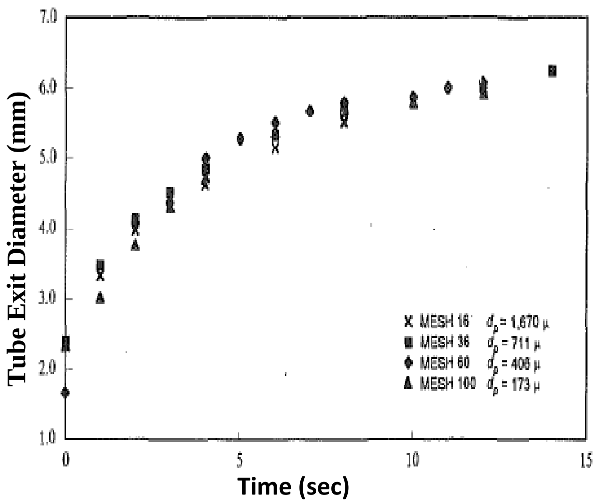
Accelerated Wear Tests Using Al_2O_3 Abrasive:

Effect of Mixing Tube Length:

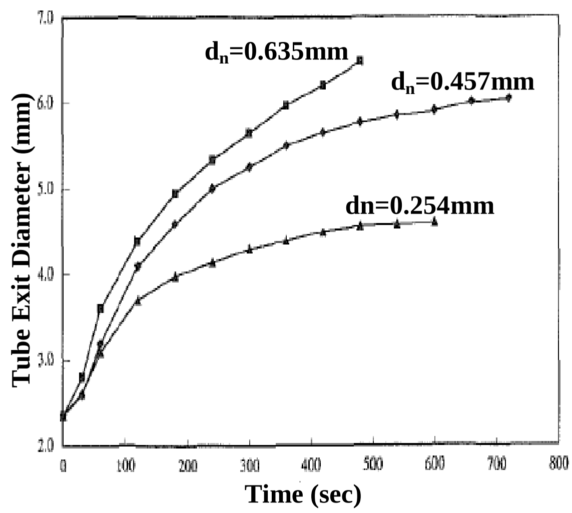
From fig.3 the longer the mixing tube, the slower the wear rate at the exit section. When the tube length increases, the velocity vectors of the particles become parallel to the wall and shallow angle impact and abrasion modes of erosion will be dominant. In this calculation taken parameters- P=207MPa, d_n=0.457mm, d_m=1.58mm, $m_{a=}$7.5g/s, mesh 60 (d_p=406 µ).

Effect of Mixing Tube Material:

From fig.4 the data showed the boron carbide (hardest material used) was the most wear resistant. Aluminum ceramic and α-silicon carbide exhibit higher wear rates than conventional C2-grade tungsten carbide, even though they were both harder than tungsten carbide. In this test taken parameters- P=207MPa, d_n=0.635mm, d_m≅3mm, l_m=51mm, m_a=36g/s, mesh 36 (d_p=710 µ).



(Fig. 1)



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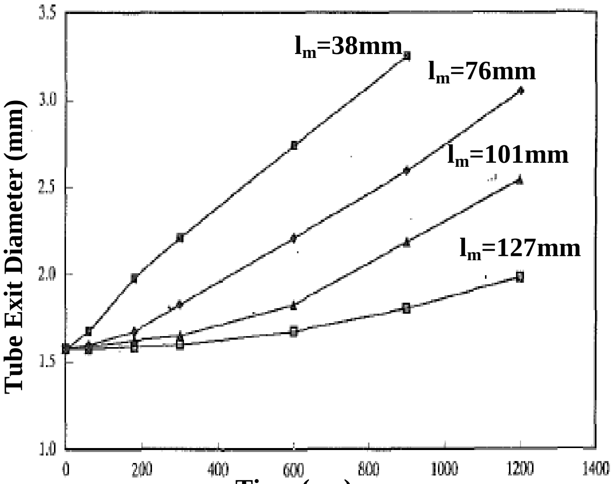

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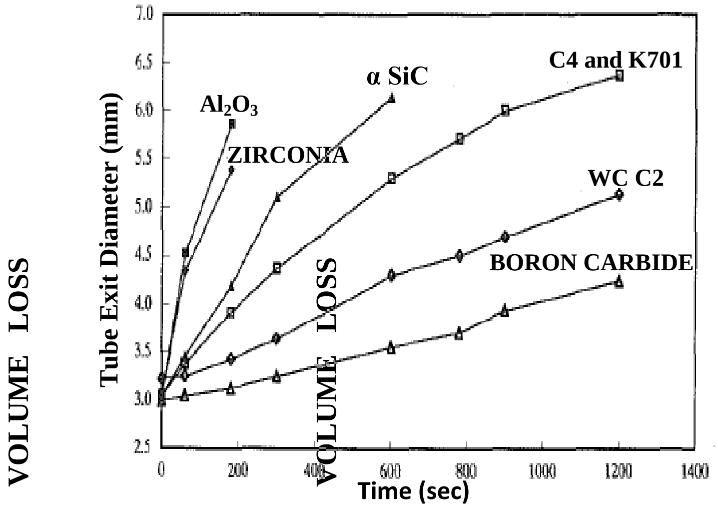


(Fig. 4)

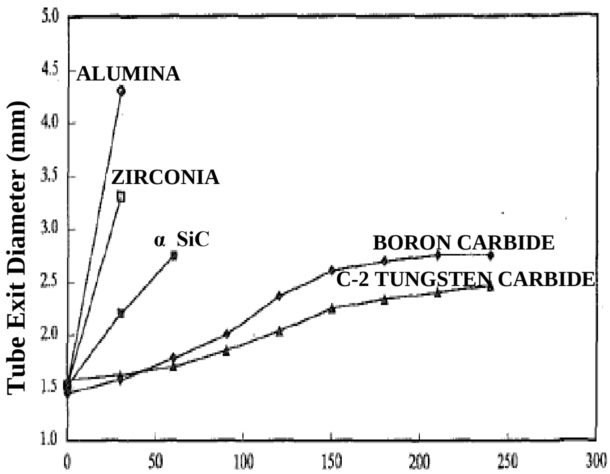
Actual-Condition Wear Tests (with Garnet)

Effect of Mixing Tube Material:

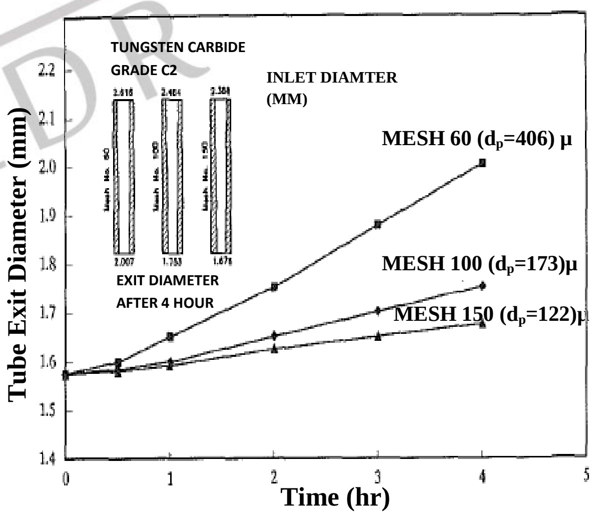
From fig.5 the result was boron carbide tube exhibited a faster wear rate than the tungsten carbide tube, which is contrary to the case when aluminum oxide was used. In this test taken parameters- P=207MPa, d_n=0.457mm, dm=1.5mm, l_m=51mm, m_a=8.4g/s, mesh 60 (d_p=406 µ).

Effect of Particle Size:

In Fig.6 showed that the reduction in wear rate as the particle size decreases. The relatively low resistance of steel tubes to erosion makes the effect of particle size insignificant, as the threshold conditions for steel wear were exceeded in all cases. In fig. 6 finer abrasive result in less wear at the upstream section, which was mostly subjected to large angles of impact.



(Fig. 5)

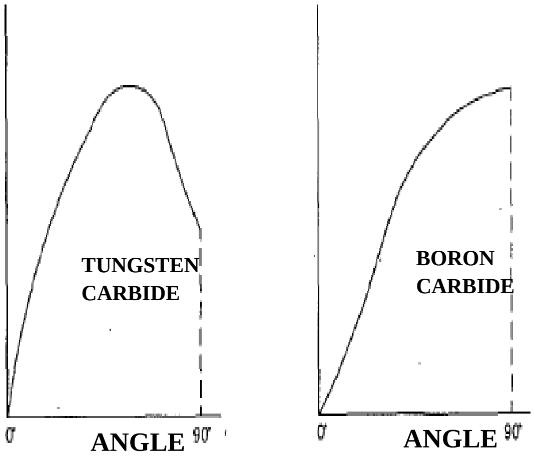


(Fig. 6)

Effect of Mixing Tube Length:

Fig. 7 showed that the longer the mixing tube, the slower the exit diameter wear rate and it indicted the potential economical advantage of using longer tubes.

In fig.8 showed the qualitative dependency of material removal by erosion for both boron carbide and tungsten carbide and showed the weakness of boron carbide to erosion as the impact angle increases.



(Fig.8)

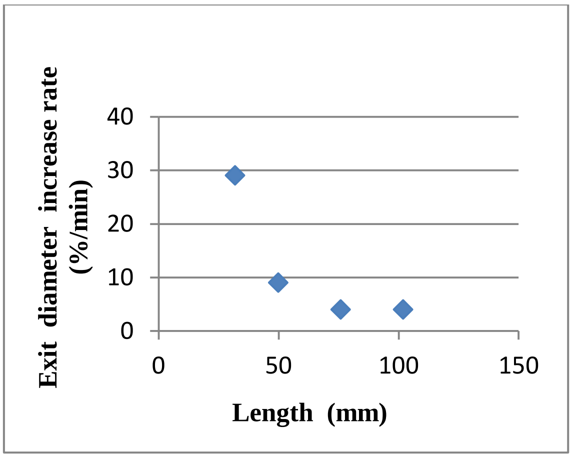
Results of this study were to improve nozzle lifetime and some conclusions is given below:

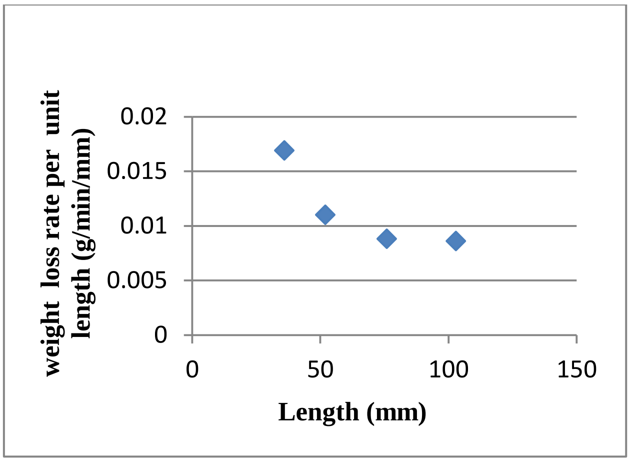
- High value of hardness and toughness of abrasive waterjet nozzle material were important for effective performance. High hardness alone or high toughness is not sufficient. Quantitative property identification is needed.
- Tube made with tough section at the entry and a hard section at the exit has an improved wear performance.

M. Nanduri et al. (2002) [2] analyzed experimentally nozzle wear in abrasive waterjet machining process. Accelerated wear test was applied, varying each parameters independently on abrasive waterjet machining where test parameters were taken during experiments Nozzle material-WC/Co, ROCTEC(R100,REXP),Abrasives– aluminum oxide, garnet.

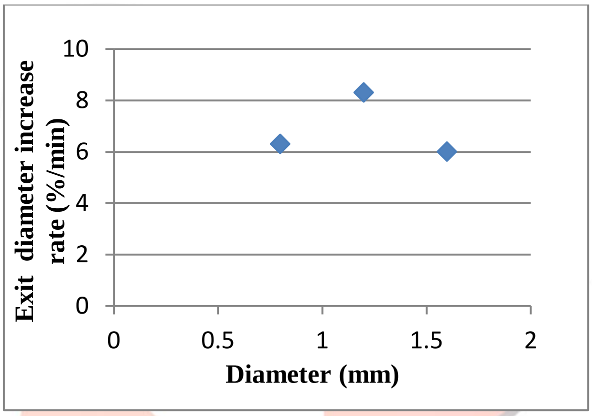
Geometrical parameters		
Parameters	Tested value	Typical value
Nozzle length	32.5, 50.8, 76.2, 106.6mm	50.8 mm
Nozzle diameter	0.79, 1.14, 6 and 6.63 mm	1.14mm
Nozzle inlet angle	10^0, 20^0, 30^0, 40^0,50^0, 180^0	60^0
Orifice diameter	0.28, 0.33, 0.38, and 0.43mm	0.38mm
System parameter		
Water pressure	172, 241, 310, and 359 MPa	310 MPa
Abrasive flow rate	1.9, 3.8, 5.7, 7.6, 9.5, 11.4 g/s	3.8 g/s

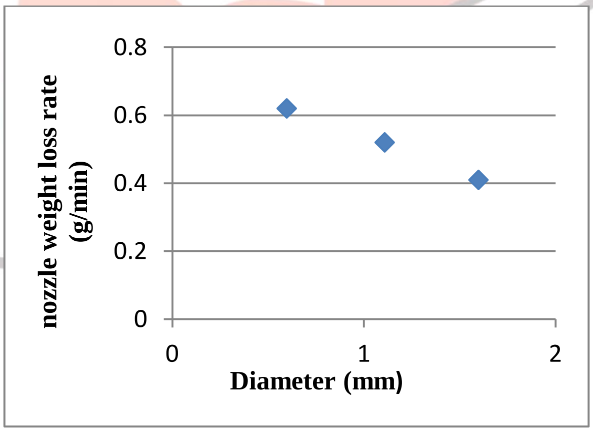
{**1**} Below fig. shows exit bore growth and weight loss rate decreases with increasing nozzle length.





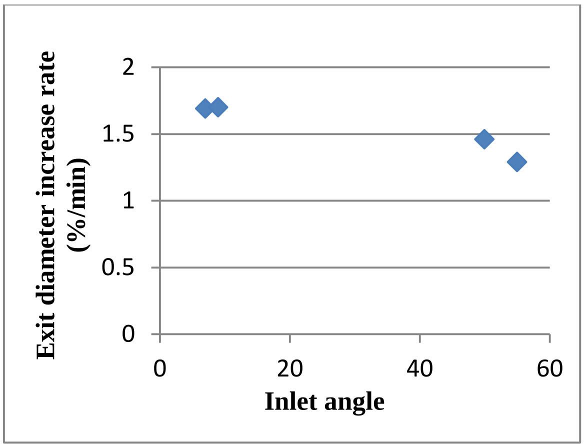
{**2**} Below fig. shows effect of bore diameter on nozzle wear. The keeping the ratio, Ro, orifice diameter to nozzle diameter around 0.3-0.4 will result in optimum mixing and cutting conditions.

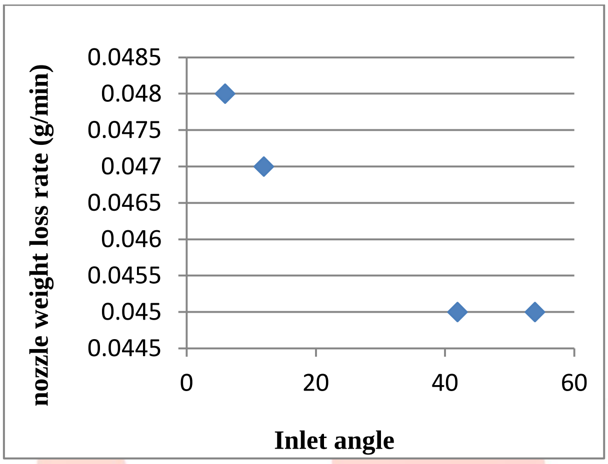




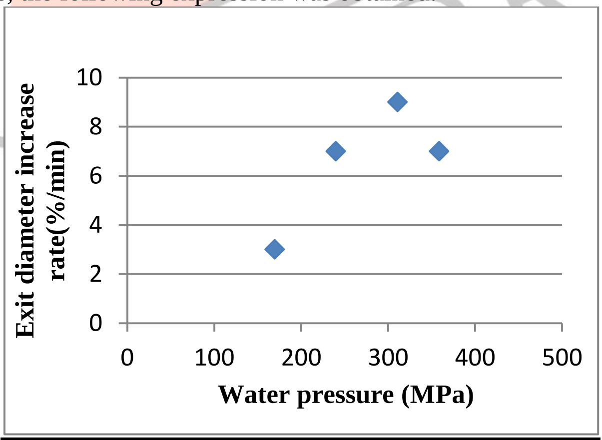
A 1.63mm diameter nozzle is too large to provide efficient moment transfer. Both cases results in reduced exit wear. A 1.14mm diameter nozzle (Ro=0.33) results in typical mixing conditions and exhibits nominal exit diameter. The weight loss curve does not exhibit the maximum seen in the exit wear curve. When Ro=0.48 then weight loss of nozzle was increased.

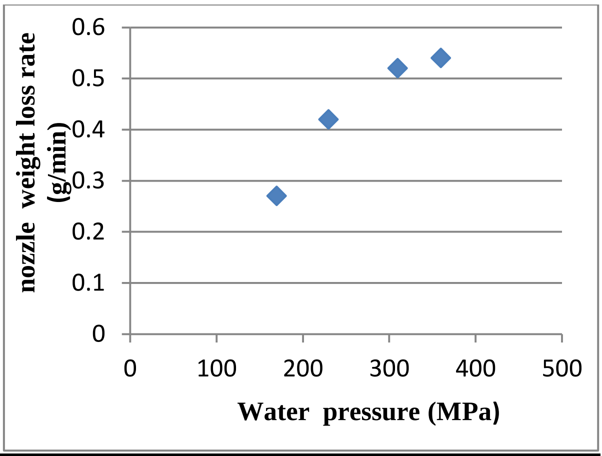
{**3**}Reduced bore growth with increasing inlet angle was observed and weight loss also decreases with increases in inlet angle.





{**4**} Exit bore profile and nozzle weight loss increases linearly with the increasing abrasive flow rate and below fig. showed nozzle weight loss and exit wear rate increases and the exit wear rate exhibit a maxima with increasing water pressure. Nozzle bore profile at 359 MPa reveal a slight reduction in wear (along the length of the bore) in comparison to the profiles at 310 MPa. To overcome this problem a wear model for erosion of nozzle materials such as WC/Co and ROCTEC 100 by AWJ. was developed, along the lines of classical erosion theories. By conducting a multiple non-linear regression analysis on the experimental data for WC/Co nozzles, the following expression was obtained:





$W_N = (8.07E\text{-}4)\,[P^{0.9}(d_o)^{0.38}\,(m_a)^{0.7} / (d_n)^{0.5}L^{0.8}]$

Where P is water pressure in Mpa and d_o and d_n are the orifice and nozzle diameters, in mm and L is the length of nozzle in mm and m_a abrasive flow rate in g/s.
Correlation between the actual experiment and predicted nozzle weight loss rates. The data correlated excellently with a correlation coefficient of 0.95. The nozzle volume loss rate, V_N for other nozzle materials may be obtained from the following relationship:
$V_N = f_N V(m_a/m_p)$, where f_N is the nozzle efficiency factor, V is the volume removed by a single particle and m_a ,m_p abrasive flow rate and mass of single particle.
The result of this paper is found the effect of nozzle length, inlet angle, diameter, orifice diameter, abrasive flow rate, and water pressure on nozzle wear studied and the nozzle wear model was developed for prediction the wear.

2. Theoretical analysis and modeling:

Jegaraj J. et al. (2005) [3] suggested a strategy for efficient and effective cutting of materials with abrasive waterjets. Efficiency and quality of the process affected due to focusing nozzle and orifice diameter undergo continuous change in their dimension. It was necessary time to time changes the dimension of focusing nozzle and orifice for achieve desired quality and maximum efficiency of process. In order to maintain the desired quality and efficiency, it was essential to monitor the condition of nozzles and orifice. In this work observed that any increase in the size of orifice bound to reduce the depth of cut and a detailed study on the influence of focusing nozzle and orifice size on the performance of abrasive waterjets. Abrasive waterjets cutting can be maintained by keeping the orifice size in the range of 0.25-0.3 mm and focusing nozzle sine in the range of 0.76-1.2 mm. The ratio of focusing nozzle size to orifice size in between 3 and 4.5. These efforts could help in building the model and strategies for adaptive control of abrasive waterjet cutting system.

D .S. Srinivasu et al. (2008) [4] presented a neuro-genetic approch proposed for selection of process parameters in abrasive waterjet cutting considering variation in diameter of focusing nozzle. In neuro-genetic approach proposed to suggest the process parameters for maintaining the desired depth of cut in abrasive waterjet (AWJ) cutting for adaptive control of AWJ cutting process and developed artificial neural network (ANN) based model for prediction of depth of cut. It is also considering the diameter of focusing nozzle along with the controllable process parameters such as water pressure, jet traverse rate, abrasive flow rate and used genetic algorithm (GA). The merits of neuro-genetic approach was shown by comparing the result obtained with the proposed approach to the result obtained by the fuzzy-genetic approach.

Development of ANN model for prediction of depth of cut the taken different process parameters employed in AWJ cutting:
The result of neuro-genetic approach to be considered as the strategy for adaptive control of AWJ cutting process in combination with a suitable system monitoring the changes in the diameter of focusing nozzle. ANN model predicting the depth of cut with any known diameter of focusing nozzle is found to be effective for complex AWJ cutting.

Parameters	Operating Range
Stand-off distance (mm)	4
Type and size of abrasive	Garnet, #120 mesh
Diameter of orifice (mm)	Φ 0.25
Number of passes	1
Water pressure (MPa)	100, 170 ,240
Abrasive flow rate(kg/min)	0.07, 0.11, 0.33
Jet traverse rate (mm/min)	30,90, 150

The efficiency of abrasive jet micromachining (AJM) process is high if the removal of hard and brittle materials at high cut quality. It is necessary in modeling the AJM process to determine the velocities of abrasive particles. **Wang et al. (2009) [5]** presented a theoretical analysis and developed a velocity model for abrasive jet micromachining. In modeling the process, the kinetic energy of abrasive particles is crucial to the plastic deformation and crack generation and erosion rate of material is dependent on the particle impact velocity. Particle velocity is a function of particle size, particle density, and gas pressure. The mathematical models for abrasive particle velocities in an AWJ were developed. The models are finally verified by comparing the particle velocities from the models with those from a particle image velocimetry (PIV) experiment.

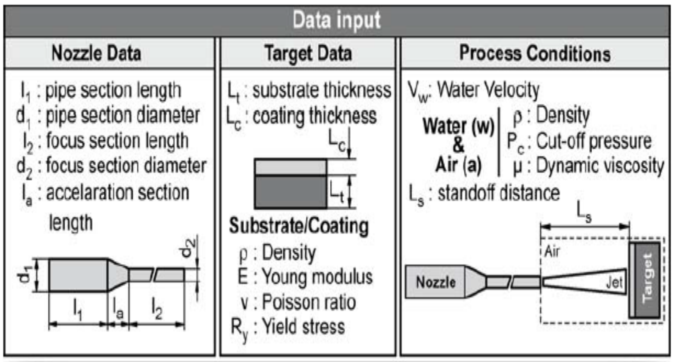
When examined particle velocity distribution in different jet cross-section the agreement between the calculated and measured results was again good. The particle velocity at the nozzle exit was modeled. The models had finally been experimentally verified by comparing the calculated and measured particle velocity data. It had been seen that model prediction are in good agreement with the experimental results with less than 4% average error and can provide an essential means for the evaluation of particle velocities required in modeling the material erosion in AJM. The result an increase in the air pressure, hence the particle velocity, will increase the magnitude of the error such as in case of 0.69MPa.

3. Software used for analysis

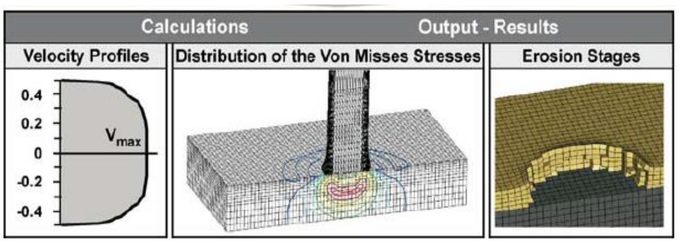
H. Liu et al (2004) [6] studied a abrasive waterjet characteristics by CFD simulation and CFD models produced for abrasive waterjet and ultrahigh velocity waterjets were established using the Fluent6 flow solver. Particle and water velocities were obtained under different input and boundary conditions to provide an insight into the jet characteristics and a fundamental understanding of the kerf formation process in AWJ cutting. For the range of downstream distances considered, the results indicate that a jet is characterized by an initial rapid decay of the axial velocity at the jet centre while the cross-sectional flow evolves towards a top-hat profile downstream. Jet dynamic characteristics for the flow downstream from a very fine nozzle are then simulated under steady state, turbulent, two-phase and three-phase flow conditions.

Kyriaki et al. (2007) [7] proposed a finite element-based model for pure waterjet process simulation and the main objective was to investigate and analyzed in detail the workpiece material behavior under waterjet impingement; a non-linear FE model (using LS-DYNA 3D code) had been developed which simulates the erosion of the target material caused by the high pressure waterjet flow .The flow has been divided into three region: inside the waterjet nozzle, the waterjet flow into the air, and the waterjet impacts on a non-moving target material. For the simulation procedure used in table 1 data and coated with polyurethane coating or non coated target material used.

Table 1



The model determines the produced velocity profiles, the distribution of the von-Misses stresses on the non-coated target, and the erosion stages of the coated target showed in below fig.



For simulation procedure the values in the water, air and target's properties used in the computational was given in below table.

	Density(ρ)(kg/m	**Cut-off pressure (P_c) (Pa)**	**Dynamic viscosity(μ) (Pa·s)**

Water	1,000	-10^5	10^{-3}
Air	1.29	-10	$1.67 \cdot 10^{-5}$
	Density(ρ) (kg/m^3)	**Young Modulus(I (Gpa)**	**Poisson ratio(v)**
A2024T3	2,700	73	0.33
Polyurethane	1,200	0.90	0.25

<u>Modeling:</u>

ICEM advanced meshing was used to mesh the whole system of nozzle, air and target. The main aim was to develop a fine mesh near the wall of the nozzle in order to gain better accuracy in velocity profile and mesh at the surface of the target was intended to be very fine so that the erosion stage can be precisely computed. Parameters taken for simulation procedure was: pipe section length and diameter were 6 and 3 mm, respectively and the accelerated length was 2mm, and the focus section length and diameter are 20 and 1 mm respectively. The waterjet velocity V_W was uniform and has value of 100 m/s at the entrance of the waterjet nozzle and the standoff distance was 2mm. The pressure was given by:

$P = K_0+K_1\alpha+K_2\alpha^2+K_3\alpha^3+(K_4+K_5\alpha+K_6\alpha^2)\, e$, Where e is the internal energy per volume, $K_0,\ldots K_6$ were coefficients for each fluid that are used from given below table;

	K_0	K_1	K_2	K_3	K_4	K_5	K_6
Water	0	2.2	9.54	14.57	0.28	0.28	0
Air	0	0	0	0	0.401	0.401	0

Boundary conditions:

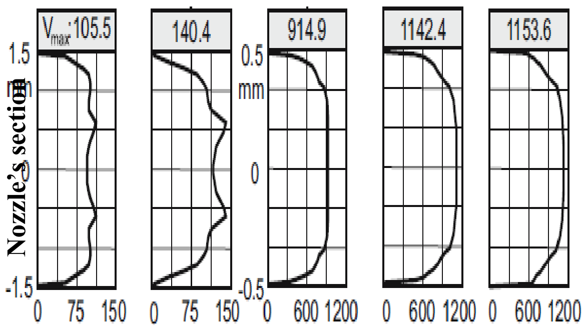
- To reduce calculations time we were focused on the half model, because of its symmetry.
- The nozzle is rigid and all six degrees of freedom were constrained.
- Automatic free boundaries were defined in the ehole mesh and at the lowest part of the target node allowed and input waterjet has a uniform velocity equal to at 100 m/s.

<u>**Simulation result:**</u>

<u>Velocity profile at various across the nozzle and across the volume fraction:</u>

Input data: d_1=3mm, l_1=6mm, d_2=1mm, l_2=20mm, l_a=2mm, V_W=100m/s, L_c=0mm, L_t=1.1mm, L_s=2mm

Below fig. showed the velocity profiles across the nozzle at various distances at a certain time stamp (0.239 ms after the uniform velocity is exerted at the inlet of the waterjet)



Entry pipe section (d_1= 3mm) **Focus section (d_2=1mm)**

It is apparent that as the waterjet expands while it is in the standoff region, the jet velocity decreases as the jet reaches the surface.

The result of model is validated by experimental results in the literatures and this proves the validity of model. In this paper investigated the material behavior under waterjet impingement on a polyurethane coated aluminum target. The erosion stage that was presented was in agreement with the literature. The simulation model can provide a lot of results to the user and it can be useful in studying the overall waterjet process and for the optimization of the waterjet parameters.

Mostofa et al. (2010) [**8**] presented a CFD analysis of abrasive waterjet cutting head and give theoretical analyses to optimize the mixing of components by multi-phase approach. This modeling was used to particle tracking was conducted to monitor the erosion rate density at the nozzle wall and predict the influence of abrasive particle and air on the mixing at different distances within the mixing tube. The k-€ turbulence model was for simulation of the abrasive particle coupled with air. ANSYS CFX 11.0 was used for the computational fluid dynamics (CFD) simulation; where investigation was done on the waterjet air abrasive velocity, as well as the erosion in the focusing tube by varying the mass flow rate of the abrasive and shape factor of the abrasive particles. Shape factor is an important parameter for abrasive particles, a circular particle has a maximum shape factor of 1.0 the more irregular the particle is, the lower its shape factor. Erosion was investigated by changing the shape factor of abrasive particles.

For CFD simulation 3-D model of the cutting head was designed and table 1 shows the geometrical and boundary conditions for the CFD analysis.

The maximum velocity of water determined in the CFD analysis was 735 m/s at the orifice exit. Velocity increases with the length of the focusing tube.CFD simulation showed the vortex created inside the mixing chamber.

Table

Boundary conditions	**Parameter**
Geometry	Orifice dia.=096mm,coefficient of discharge, C_d=0.8
	Mixing chamber dia.=4.2, length=3mm
	Focus tube dia.=1.5mm, length=70mm
	abrasive inlet dia.=1.56mm
Boundary conditions	Abrasive mass flow rate=8,20,30 g/s density=7854kg/m^3
	shape factor=1,0.9,0.7, air velocity=5m/s
	water pressure=470MPa, density=1134kg/m^3,v_o=1.0m/s
	Fluid solid coupling=one way coupled and fully coupled

Shape factor has an effect on abrasive velocity & erosion rate.

Shape factor	**Max. Erosion(kg/m^2)×10^8**	**Velocity of abrasive(m/s)**
1	0.96	299.9
0.9	1.45	305
0.7	2.48	309.5

The analysis result showed that erosion rate increases on the focusing tube wall with the change in the particle shape factor and mass flow rate of abrasive is very high then the efficiency of jet decreases. And result showed the nozzle length has an effect on the mixing of abrasives water and air and that the velocity of the waterjet influences the erosion rate at the nozzle wall.

Mehdi Zohoor et al. (2012) [9] developed of an algorithm for control process to compensate the nozzle wear effect in cutting the hard material using abrasive waterjet cutting process. Nozzle diameter is important factor for good surface quality of workpiece, due to nozzle wearing throughout cutting process, cause a decrease in surface quality and increase in kerf width.

This paper related to series of experiments had been done to determine the effect of process parameters and the results showed that traverse speed were significant parameters on kerf geometry and quality. Experimental and analytical results showed effective parameters in kerf quality and geometry was including: nozzle diameter, traverses speed, and water pressure, but abrasive flow rate, in a selected range, is considered as an effective factor. A control program algorithm was suggested to compensate the effect of nozzle diameter increase on cut surface quality and kerf width. Accordingly, parameters controlled by system control program, can change, and if products dimension do not match with their allowable dimensions, the control program creates an offset with required amount in nozzle path. This is done to produce products in allowable dimensions.

III.SUMMERY

All experimental analysis and investigations had done on AWJM process. Quality of cutting surface in AWJM is depending on so many process parameters. Production is improved by improving the traverse speed but major problem with increasing traverse speed is that the nozzle wear is started and the flow of jet is not proper then surface roughness and kerf quality are decreased. Types of nozzle and nozzle materials affect the efficiency of AWJM process. Abrasive flow rate and types of abrasive also affect the production or MRR.

IV.CONCLUSION

Efficiency of AWJM process is depending on nozzle wear and nozzle wear is depending on so many process parameter and geometrical parameters. Process parameter which affect less or more on quality of cutting AWJM are hydraulic pressure, abrasive flow rate, size of abrasive, standoff distance and geometrical parameter as a nozzle length, nozzle diameter, and nozzle inlet angle, orifice size. Nozzle wear is measured by % exit bore diameter rate and % volume loss rate of nozzle and quality of cutting surface is measured by material removal rate, surface roughness, kerf width, kerf taper ratio.

From the literature review compare to all mentioned parameters traverse speed is most effective parameter for MRR. Abrasive flow rate is also an important parameter for increasing MRR. But beyond some limit with increase in abrasive flow rate and traverse speed the surface roughness decreases. Increasing traverse speed also increase the kerf geometry and nozzle wear increases. So it is required to find optimum condition for process parameter to give better quality of cutting surface.

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