iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 Issue: XI Month of publication: November 2021

DOI: https://doi.org/10.22214/ijraset.2021.38952

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue XI Nov 2021- Available at www.ijraset.com

Mathematical Modelling and Experimental Investigation of Abrasive Jet Machining for Various Abrasive Particles

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Abstract: Abrasive water-jet machining operates by the impingements of a high velocity abrasive laden water-jet against the work piece. The jet is formed by mixing abrasive particles with high-velocity water in the mixing region and is forced through the orifice. The accelerated jet exiting the nozzle travels at a very high velocity and cuts as it passes through the work piece. It is a difficult task of predicting the values of major cutting performance measures in Abrasive Water Jet (AWJ) cutting. AWJ cutting process involves a large number of process and material parameters, which are related to the water-jet, the abrasive particles, and work-piece material. Those parameters are expected to affect the material removal rates and depth of penetration. In this paper, various models of wear by particle erosion and the most accepted models for predicting the depth of penetration in AWJ cutting are reviewed. However, there has been very little reported study on AWJ machining using various abrasive particles. In this paper, an attempt has been made for the development of the predictive mathematical model for AWJ cutting with various abrasive particles having different geometrical shapes and physical properties. Also, their effect on the target material has also been studied. Afterward, this model is verified with the experimental investigation.
Keywords: AWJM, Abrasive, Mathematical-Modelling, Manufacturing, Water-Jet

I. INTRODUCTION

The best of the AJM and WJM processes are combined to create a process known as an abrasive water jet machine. The application of this process is used to machine the hard material at high rates. Now a day's abrasive water jet machining technology is considered to be one of the most developing advanced non-traditional methods used in industry for material processing with distinct advantages of no thermal distortion, high machining versatility, high flexible and small cutting forces. The abrasive water jet machining process is most suitable for machining a wide range of materials like brittle, glass, ceramic, stones, composites material, ferrous and non-ferrous alloys. Conventional machining or shaping methods result in very high machining cost and degradation of strength and some useful properties. So, need to develop a process capable of giving adequate material removal rate as well as minimum damage to the material. In 1968 the water jet technology was invented by Dr. Norman Franz. In 1980 Dr. Hashish added the abrasive to plain water stream then after the abrasive water jet was invented for the first time and it is widely used for machining hard materials like ceramic and composites. A stream of small abrasive particles is introduced in the water jet in such a manner that the water jet's momentum is partly transferred to the abrasive particles. A stream of small abrasive particles is introduced in the water jet in such a manner that the water jet's momentum is partly transferred to the abrasive particles. The main advantages of this process include Omnidirectional cutting, minimum thermal damage, no burs, high cutting speed and efficiency, and suitability for automation. Some disadvantages of this technique include low nozzle life, equipment cost, the hazard from the rebounding abrasives.

A. Working Principle

Abrasive water jet machining is based on the principle of water erosion. When a high-velocity jet of water strikes the surface, the removal of material takes place. Water jet machining is used for softer material but it is used for harder material by adding abrasive particles in water jet machining.

B. Component of Abrasive Jet Machine: (Refer Fig. 1)

1) Polymer adder
2) Booster pump
3) Filter

4) Intensifier
5) Hydraulic pump
6) On-off pump
7) Nozzle
8) Catcher

A Hydraulic intensifier is a device which is used to increase the intensity of pressure of any hydraulic fluid or water, with the help of the hydraulic energy available from a huge quantity of water or hydraulic fluid at a low pressure. These devices are very important in the case of hydraulic machines, mainly hydraulic presses, which require water or hydraulic fluid at very high pressure which cannot be obtained from the main supply directly. The potential applications of AWJM are numerous. Because of the technical and economic performance of abrasive water jet, many industries could immediately benefit from this new technology. Over the last decades, AWJM has been found to be widely used in various industries, including manufacturing industry, civil and construction industry, coal mining industry, food processing industry, oil and gas industry, electronic industry and cleaning industry. Abrasive water jet cutting is highly used in aerospace, automotive and electronics industries. In aerospace industries, parts such as titanium bodies for military aircrafts, engine components (aluminum, titanium, heat resistant alloys, and stainless steel), aluminum body parts and interior cabin parts are made using abrasive water jet cutting. AWJM has been particularly used in cutting "difficult-to-cut" materials.

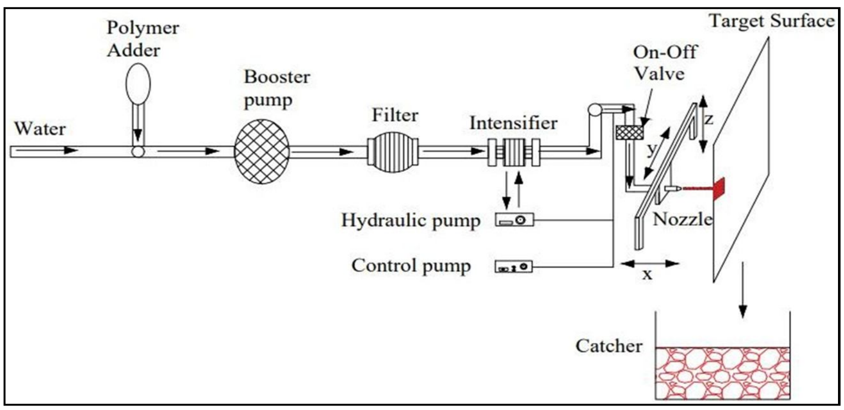

Fig. 1 Schematic Diagram of Abrasive Jet Machining (AWJ)

II. LITERATURE SURVEY

A. *Introductory Survey*

In 1968, Dr. Norman Franz [1] invented the water jet technology. AWJ development started in the early '80s of the 20th century. In 1980, Dr. Hashish added the abrasive in the plain water jet and then after abrasive water jet technology was invented for the first time to cut the industrial material such as steel, glass, and concrete. In 1983, the idea of the entraining abrasive particle in water stream was widely employed and immediately followed by the invention and development of the first commercial AWJ system for cutting automotive glasses. In 1983, its first industrial application. The high-pressure abrasive water jet was first commercialized in 1983 used in industry for linear cutting and piercing of steel, cast iron, super alloys, glass, and composites. In 1984 M. Hashish [2] used to erosion model of Finnie to develop a model to predict the combined depth of cut due to cutting and deformation for ductile material only. However, this erosion model does not incorporate the effect of abrasive particle size and shape. In 1989 M. Hashish [3] developed an improved erosion model by expanding Finnie's model to include the effect of the abrasive particle size and shape expressed by spherical and roundness. This model is predicting the depth of cut due to the cutting wear while the prediction of depth of cut due to deformation wear is based on bitter's model. In 1998, S. Paul [4] developed an analytically model of generalized kerf shape for ductile material considering variation in kerf width along with its depth.S. Paul [5] also developed a complex mathematical model for a total depth of cut for polycrystalline brittle material accounting for the effect of abrasive size and shape but neglecting the variation of kerf width along with the depth of cut. In 1999 J. Wang[6] developed a model for machining polymer matrix composites and improving the material removal rate from the workpiece is proportional to the kinetic energy of the abrasive particle. In 2007 A. Henning, E. Westkämper [7] had done the dynamic analysis of the spatial-temporal behavior of the cutting front in AWJ cutting.

This new approach towards the analysis of the abrasive water jet cutting process has presented. For the first time it is now cutting the front and to gain substantial new insights about the behavior of the cutting process. In 2010 Mustafa Ay, Ulas Caydas & Ahmet Hascalik [8] study the effect of traverse speed on abrasive water jet machining of age-hardened Inconel 718 Nickle based superalloy. As a result, with an increase in traverse speed the kerf taper angle is also increased. In 2011 Predreg Jankovic [9] improve the cut quality of abrasive water jet machining by changing many process parameters and also describe that the surface has a better character in the region that begins to cut to the middle of the thickness. The two-dimensional dynamic photoelasticity method was developed by Ramulu to record the photoelastic stress pattern associated with AWJ drilling and cutting. These fringe patterns were used to identify the transient stress field adjacent to the drilled hole during the initial caster generation and crack propagation. Hocheng and K.R. Chang [10] have carried out work on the kerf formation of a ceramic plate cut by an abrasive water jet. A sufficient supply of hydraulic energy, fine mesh abrasive at moderate speed gives smooth kerf surface. By experiment, they find that kerf width increases with an increase in pressure & traverse speed. M.A. Azmir, A.K. Ahsan [11] had done practically for surface roughness and a kerf taper ratio of glass composite laminate machined by AWJM. They use the Taguchi method and ANOVA for optimization. Ahmet Hascalik, Ulas Aydas, Hakan Gurun [12] has carried out a study on the effect of traverse speed on abrasive water jet machining of Ti- 6Al-4V alloy. They perform practical by varying traverse speeds of 60, 80, 120, 150, 200, and 250 mm/min by abrasive water jet (AWJ) machining. They studied the effect of traverse speed on the profiles of machined surfaces, kerf geometries, and microstructure features of the machined surfaces. A.A. Khan, M.M. Hague [13] analyzes the performance of different abrasive materials during abrasive water jet machining of glass. They make a comparative analysis of the performance of garnet, aluminum oxide, and silicon carbide abrasive in abrasive water-jet machining of glass. The hardness of the abrasives was 1350, 2100, and 2500 knops, respectively. Hardness is an important character of the abrasives that affect the cut geometry. The depth of penetration of the jet increases with the increase in the hardness of the abrasives. J. John Rozario Jegaraj, N. Ramesh Babu [14] had worked on a strategy for efficient and quality of materials with abrasive water jets considering the variation in the orifice and focusing nozzle diameter in cutting 6063-T6 aluminum alloy. They found the effect of orifice size and focusing nozzle diameter on the depth of cut, material removal rate, cutting efficiency, kerf geometry, and surface roughness. The ratio of 3:1 between focusing nozzle diameter to orifice size was suggested as the best-suited combination out of several combinations of focusing nozzle to orifice size to achieve the maximum depth of cut in cutting. Mahabalesh Palleda [15] investigated the effects of the different chemical environments like acid polymer phosphoric and acetone, (polyacrylamide) in the ratio of 30% with 70 % of water and standoff distance on the taper angles and material removal rates of drilled holes in the abrasive water jet machining process. Material removal is highest when the slurry is added with polymer compared to three slurries. PK Ray and Dr. A K Paul[16] had investigated that the MRR increases with an increase of air pressure, grain size, and with an increase in nozzle diameter. MRR increases with an increase in standoff distance (SOD) at a particular pressure. They found after work that initially MRR increases and then it is almost constant for small range and after that MRR decreased as SOD increase. In 2017 Miroslav R. Radovanović[17] work on Performances of Abrasive Water Jet Cutting with Hyper Pressure Abrasive water jet cutting machines operating with hyper pressure of 600 MPa have better performances versus abrasive water jet cutting machines operating with high and ultra-high pressure. Increasing pressure of 380 MPa to 600 MPa significantly improves water jet cutting productivity and reduces machining costs.

B. Process Parameter Review

In 1998 Jun Wang [18], Are study of polymer matrix composites using abrasive water jet cold cutting technology. An experimental investigation of the machinability and kerf characteristics of polymer matrix composite sheets under AWJ is present. In work, the top and bottom kerf widths for all of the cuts were measured with a ‘Carl zeiss’ universal measuring microscope. The conclusion is the combination of process parameters recommended for the material under consideration may be used for maximizing productivity whilst maintaining good kerf quality in practice. In 2007 mahabalesh palleda[19], study the effect of using different chemicals on material removal rate, with varied standoff distance and chemical concentration in AWJM. They are proved that by increasing MRR and decreasing taperness by varying S.O.D. with the different chemical environments and chemical concentration the maximum material removal was observed at S.O.D 4.5mm using plain water in the slurry at 4mm acetone with slurry and 3.5mm for slurry mixed with phosphoric acid. Above MRR indicates more effectiveness. But slurry added with polymer shoes highest MRR than others. The increase in MRR obtained using a chemical environment like acetone and phosphoric acid indicates the effect of hydrogen in enhancing crucks formed due to the impact of an abrasive particle on the work material. In 2008 D. K. Shaninugam and S. H. Masood[20], they have studied kerf characteristics in AWJ cutting of layered composites. There is an investigation on the kerf taper angle an important cutting performance measure generated by AWJ technique to the machine.

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Two types of composites epoxy and pre-impregnated graphite, fabric and glass epoxy are used. They use dimensional technique and an energy conservation approach the kerf taper angle has been related to the operating parameter in form of the predictive model.

$$y = \left(\frac{sd}{dj}\right)^{0.451} * \left(\frac{Edj^2}{Vt\ Ma}\right)^{-1.23} * \left(\frac{p}{\rho w} * \frac{Ma^2}{dj\ E^2}\right)^{-0.84}$$

Here prove that a combination of high water pressure, low traverse speed, and low standoff distance is recommended to minimize the kerf angle. In 2008 M. A. Azmir [21], they have studied the effect of AWJ machining parameters on ceramic fiber-reinforced plastic composite. They are studying the effect of the AWJM process parameter on surface roughness(Ra) and kerf taper ratio(Tr) of the AFRP composite. It was found that the traverse rate was considered to be the most significant factor in both Ra and Tr quality criteria. It was found Ra and Tr were reducing at that time increasing hydraulic pressure and reducing the S.O.D. and traverse rate. So, increasing the kinetic energy of the water jet may produce better quality cuts. It was proved that the increase the pressure at that time Ra and Tr are decrees and S.O.D., traverse rate is effected as the opposite. In 2011 M. Chithirai Pon Selvan & N. Mohana Sundara Raju [22] they study about the Influence of process parameters on Depth of Cut which is an Important Cutting Performance measure in AWJ cutting of Stainless Steel, Cast iron, Granite, and Ceramics. The process variables considered here include traverse speed, abrasive flow rate, Standoff distance, and Water pressure To Correctly select the process parameters an Empirical model for the prediction of depth of cut in AWJ cutting of specimen is developed using regression analysis. This developed model has been verified with the experimental results that reveal the High applicability of the model within the experimental range used. The developed model is finally assessed using the experimental data and found to be able to give adequate predictions within the experimental range considered in this study. As a result of this study, it is observed that these operational parameters have a direct effect on the depth of Cut. Also, verification of the developed model for using it as a practical guideline for selecting the parameters has been found to agree with the experiment. In the year 2012Mgent, M. Menedez, S. Torno, J. Toruno[23]are find the experimental evaluation of the physical properties required of abrasive for optimizing Water jet cutting of ductile material. The polycrystalline abrasive (Diamond) Are more effective than monocrystalline abrasive of the same composition. There is also a linear relationship between the Vicker's Hardness of abrasive and the rate of an Abrasive and the rate of an Abrasive and the rate of erosion and that the more angular the abrasive particle edge the greater the rate of erosion.

$$Y = 0.01693*\ln(x)-0.03172$$

$$Y=0.01875*\ln(x)-0.0514$$

Averaged equation; $$Y=0.01784*\ln(x)-B$$

Where,

Y=Rate of erosion

X=feed rate

B=constant particularly to each abrasive

It is proven that with the same abrasive mass flow rate fewer larger particles erode more rapidly than a greater number of finer particles of the same composition. In the year 2012 [24] the article presented regarding the technique of Abrasive water jet cutting and permanence of this type of technology by Cristian Brita and valeriu avramescu. There are presented also results regrading other than cutting technological operations possible to be performed with the abrasive water jet. It can be observed that the efficiency of the process (depth of cut) increases with an increase of pressure regardless of material. It also observed that that increase in cutting speed decrease the cut depth. The depth of cut increases with the piece distance near to the jet. In 2012 M. Chithirai Pon Selvan & N. Mohana Sundara Raju[25], they study about the Influence of process parameters on Surface Roughness (Ra) which is an important cutting performance measure in AWJ cutting of Cast iron and Aluminium Taguchi's design of experiments was carried out to collect Surface Roughness Values. The use of High water pressure is preferred to obtain Good Surface Finish. This experimental study has resulted from surface Smoothness Increase as Standoff distance decreases. Therefore, to achieve an overall cutting performance, a low Standoff distance should be selected. In the year 2015[26] the effects of the jet impact angle on the cutting performance in abrasive water jet machining of alumina ceramics is presented based on an experimental investigation by J. Wang. It is found that inclining the jet forwarding the cutting plane is an effective means in improving the cutting performances. It uses multi-pass Abrasive jet machining and finds effective cuttings performance. He is prove that depth of the cut increase significantly as the jet impact angle is 60`to 80`.the jet angle beyond 80 has resulted in a decrease in the depth of the cut.

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So optimum jet impact angle is about 80`.this jet angle can considerably increase the Depth of cut by up to more than 20%in single pass cutting when compared to those with 90`jet impact angle. In 2018 Niranjan C. A, Srinivas S., Ramachandra M.[27] are work 0n An Experimental study of depth of cut of AZ91 Magnesium Alloy in AWJ cutting, New approach of finding the depth of cut using profile projector has been used in this study The effect of process parameters on depth of cut was Investigated through Taguchi's experimental design of 19 Orthogonal arrays, The present study concludes the use of a profile projector for measuring Length of cuts is most accurate than other methods & AWJ cutting is the most viable and effective alternative for Risk-free machining of Magnesium alloy. In 2019 R. Shibin, V. Anandakrishnan[28] are studied in Investigation on the AWJ machinability of AA2014 using Silicon Carbide as Abrasive. The selected parameters were varied at three levels & a 19 Orthogonal design was developed. Based on this, filling up the developed design the AWJ cutting was performed on the Aluminium alloy and the Depth of cut was measured & analyzed using Taguchi's quality characteristic "Large the better". The conclusion is the optimum AWJ machining parameters to achieve the Higher DOC are recognized as 100 mm/min Traverse speed, 1.5 mm Standoff distance, 350Mpa Pressure, and 0.550 kg/min mass flow rate.

III.PROCESS PARAMETER

A vast literature published focuses their interest on the modeling of the depth of cut including the exploration of the influence of main AWJ process parameters on the depth of cut and prediction of the cutting performance. Four process parameters, i.e. water pressure, Nozzle traverse speed, mass flow rate of abrasive particles, and standoff distance. Approximately range in main parameters is below in table I.

TABLE I
PARAMETERS OF AWJM

Sr. No.	Parameters	Range
1	Water Orifice Diameter	0.25mm to 0.35mm
2	Nozzle Diameter	0.76mm to 1.05mm
3	Mixing Tube Diameter	0.5mm to 0.76mm
4	Nozzle length	70mm to 90 mm
5	Angle of Impact	60° to 90°
6	Depth of Cut	1mm to 250mm

A. *Experimental Data*

Four machining parameters has selected as shown in Table II. The machining parameters and levels has selected primarily based on the literature review of some studies that had been documented on AWJ machining of graphite/epoxy laminates, ceramic material, metallic coated sheet steels, and fiber-reinforced plastics.

Table III
Levels of parameters used in experiment

Parameters	Unit	Level 1	Level 2	Level 3
Water pressure	MPa	270	335	400
Traverse speed	mm/s	0.42	1.46	2.5
Mass flow rate	g/s	8	12	15
Standoff distance	mm	1.75	3.37	5

Based on Taguchi's method DOE, an L81 orthogonal arrays table with 81 rows (corresponding to the number of experiments) was selected for the experimentation. In the present study, only four-machining parameters were involved, therefore the remaining columns in the L81 orthogonal array were kept unused. It is also to be noted that based on the full factorial design of the experiment having four parameters each at three levels require a total number of 81 combination or experiments to be conducted. This coincides with the L81 Orthogonal arrays used in the study.

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B. *Effect of Parameters on Depth of Cut*

The effects of the four basic parameters, i.e., water pressure, abrasive mass flow rate, nozzle traverse speed, and nozzle standoff distance on the depth of cut are in the same fashion as reported in previous studies for other materials. The effect of each of these parameters is studied while keeping the other parameters considered in this study constant.

1) *Effect of water pressure on depth of cut:* An increase of water pressure increases the depth of cut when mass flow rate, traverse speed, and standoff distance were kept constant. When water pressure is increased, the jet kinetic energy increases that leads to more depth of cut.

Constant: Mass Flow Rate: 15 g/s; Transverse Speed 0.5 mm/s; Standoff Distance: 1.85 mm

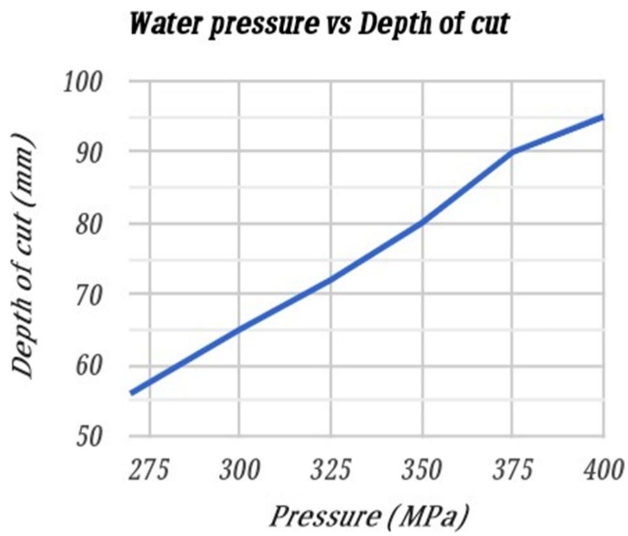

Fig. 2 Water Pressure (MPa) Vs. Depth of Cut

2) *Effect of mass flow rate on depth of cut*: An increase in abrasive mass flow rate also increases the depth of the cut. This is found while keeping the pressure, traverse speed, and standoff distance constant. The impact between the abrasive partial and the material determines. Since cutting is a cumulative process, the speed of the abrasive particles and the frequency of particle impacts are both important. The speed of the part determines the impulsive loading on the material and the potential energy transfer from the particle to the material. The frequency of the impact determines the rate of energy transfer and hence, the rate of cut depth growth. The mass flow rate of the abrasive particles partially determines the frequency of the impacting particles and partially determines the speed at which they hit. In addition, with the greater mass flow rates, the kinetic energy of the water must be spread over more particles. Therefore, the depth of the cut goes down with the increased mass flow rate.

Constant: Water pressure: 395 MPa; Transverse Speed 0.5 mm/s; Standoff Distance: 1.85 mm

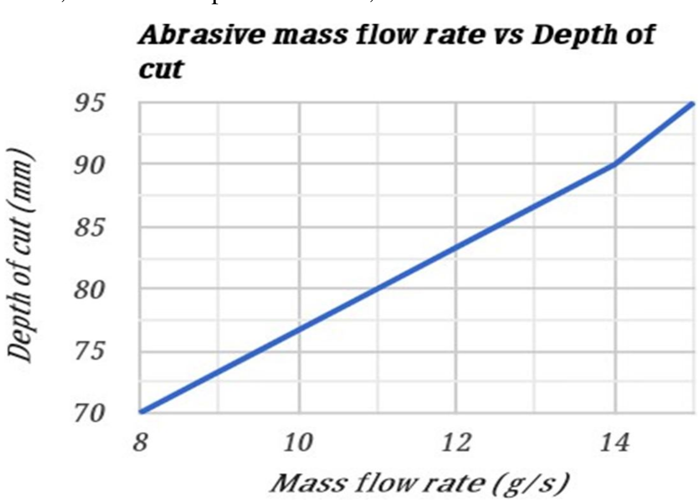

Fig. 3Abrasive mass flow rate Vs. Depth of Cut

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
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3) *Effect of Transverse Speed on Depth of Cut*: Traverse speed is the advanced rate of the nozzle on a horizontal plane per unit time during the cutting operation. An increase of traverse speed decreases the depth of cut within the operating range selected, by keeping the other parameters considered in this study constant. The longer the abrasive water jet stays at a particular location, the deeper the cut will be because the stream of abrasive particles has more time to erode the material. This effect is due to two reasons. First the longer the dwell time the greater the number of impacting abrasive partials that hit the material and the greater the microdamage, which starts the erosion secondly, the water from the jet does tend to get into the micro cracks, and because of the resulting hydrodynamic pressure, the crack growth results. When the micro-cracks grow and connect, the included material will break loose from the present material, and the depth of cut increases. For this reason, it seems reasonable to expect an inverse relationship between the traverse speed and the depth of the cut.

Constant: Water pressure: 395 MPa; Mass flow rate: 15g/s; Standoff Distance: 1.85 mm

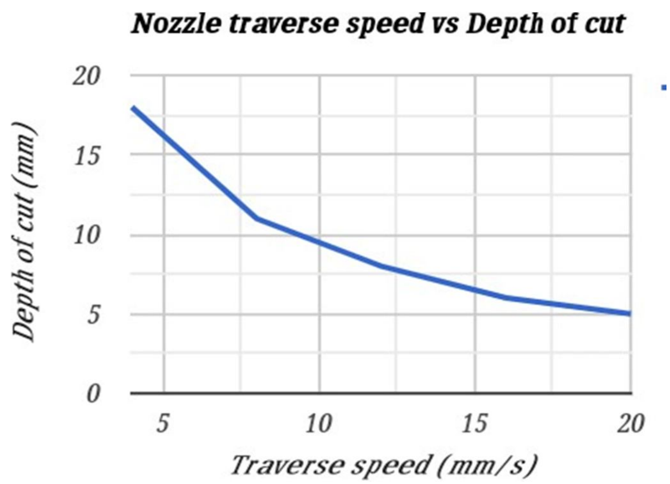


Fig. 4 Nozzle transverse speed Vs. Depth of Cut

4) *Effect of Standoff Distance on Depth of Cut*: Standoff distance is the distance between the nozzle and the work piece during the cutting operation. If we keep other operational parameters constant, when standoff distance increases, the depth of cut decrease. However, standoff distance on the depth of cut is not much influential when compared to the parameters considered in this study.

Constant: Water pressure: 395 MPa; Transverse speed: 0.5 mm/s; Mass flow rate: 15 g/s

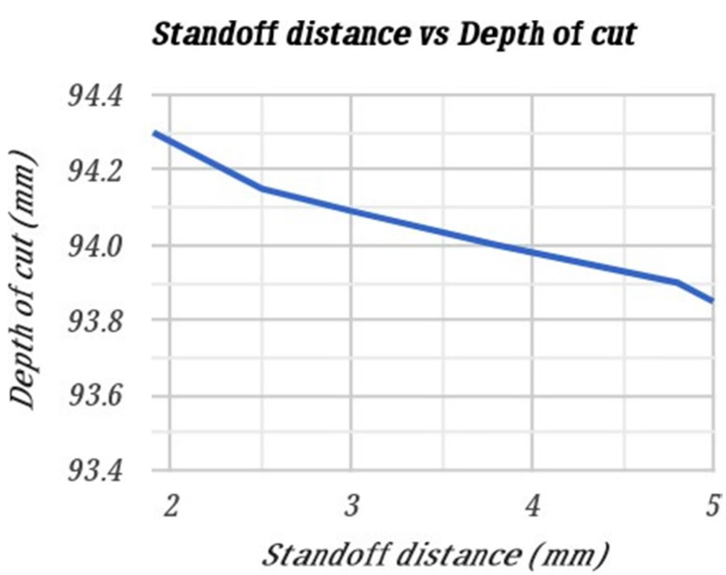


Fig.5Standoff distance Vs. Depth of Cut

IV. MODIFICATION OF MATHEMATICAL MODEL OF DEPTH OF CUT (DOC)

$$V_{WJ} = \Psi \sqrt{\left(2P_W / \rho_W \right) q_w}$$

$$V_{ab} = \left(\frac{1}{1+R} \right) V_{wj}$$

$$V_{awj} = \eta \left(\frac{1}{1+R} \right) V_{wj}$$

Mixing Ratio,

$$R = \frac{M_{ab}}{M_w}$$

$$M_{ab} = R * M_w$$

$$M_w = \rho_w * C_d * \frac{\pi}{4} * {d_0}^2 * V_{WJ}$$

Assumption,

$$P_{ab} = P_{awj} = \left(\frac{1}{2} \right) M_{ab} * {V_{awj}}^2$$

$$= \left(\frac{1}{2} R * \rho_w * C_d * \frac{\pi}{4} * {d_0}^2 * V_{WJ} \right) * {V_{awj}}^2$$

$$= \left(\frac{1}{2} R * \rho_w * C_d * \frac{\pi}{4} * {d_0}^2 * V_{WJ} \right) * \left(\left(\frac{\eta}{1+R} \right) V_{wj} \right)^2$$

$$= \left(\frac{1}{2} R * \left(\frac{\eta}{1+R} \right)^2 \rho_w * C_d * \frac{\pi}{4} * {d_0}^2 \right) * \Psi^3 * \left(\frac{2P_w}{\rho_w} \right) * \sqrt{\left(2P_W / \rho_W \right)}$$

$$= R * \left(\frac{\eta}{1+R} \right)^2 * \mathrm{K} * \frac{\pi}{4} * {d_0}^2 * {P_W}^{\frac{3}{2}} * \sqrt{\left(2P_W / \rho_W \right)}$$

$$\mathrm{MRR} = \zeta \left(\frac{P_{awj}}{u_{workpiece}} \right) = \zeta * \mathrm{K} * R * \left(\frac{1}{1+R} \right)^2 * \frac{\pi}{4} * \frac{({P_W}^{3/2}) * ({d_o}^2)}{E_m} * \sqrt{\left(2/\rho_W \right)}$$

$$\mathrm{MRR} = D_c * d_j * u$$

$$D_c = \frac{\mathrm{MRR}}{d_j * u} = \zeta * \mathrm{K} * R * \left(\frac{1}{1+R} \right)^2 * \frac{\pi}{4} * \frac{({P_W}^{3/2}) * ({d_o}^2)}{E_m * d_j * u} * \sqrt{\left(2/\rho_W \right)}$$

Empirical model for M. Chithirai Pon selvan [29] (2011) paper is,

$$D_c = 104 \left(\frac{P^{1.253} * M_a^{0.466} * d_p^{1.073} * \rho_p^{0.383}}{E^{1.102} * u^{0.768} * s^{0.005} * \rho_w * d_j} \right)$$

Modified equation,

$$D_c = 104 \left(\frac{P^{1.5} * d_0^2 * \rho_p^{0.383}}{E^{1.102} * u * s^{0.005} * d_j} \right) * R * \left(\frac{1}{1+R} \right)^2 * \sqrt{\left(2/\rho_W \right)}$$

Where,

Ψ = velocity co-efficient
η = loss of momentum
ρ_p = Abrasive particle density (kg/m3)
ρ_W = water density (kg/m3)
D_C = Depth of Cut (mm)
D_j = Jet Diameter (mm)
D_o = Orifice Diameter (mm)
E= Modulus of elasticity of material (MPa)
M_{ab} = Mass flow rate of abrasive particles (g/s)

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue XI Nov 2021- Available at www.ijraset.com

M_w= Mass flow rate of water (g/s)
P_{ab} = Abrasive pressure (MPa)
P_w = Water pressure (MPa)
P_{awj}= Abrasive water jet pressure (MPa)
u= Traverse speed of nozzle (mm/s)
R = Mixing Ratio
S = Standoff distance (mm)
V_{awj} = Velocity of abrasive water jet (mm/s)
V_{wj}= Velocity of water jet (mm/s)

V. EXPERIMENTAL INVESTIGATION

Three work pieces/specimens of Mild steel 2062 were taken each (150mm×75×mm×20mm) as shown in Figure 6 and Figure 7. Chemical analysis and physical properties of MS 2062 are tabulated in Table III.

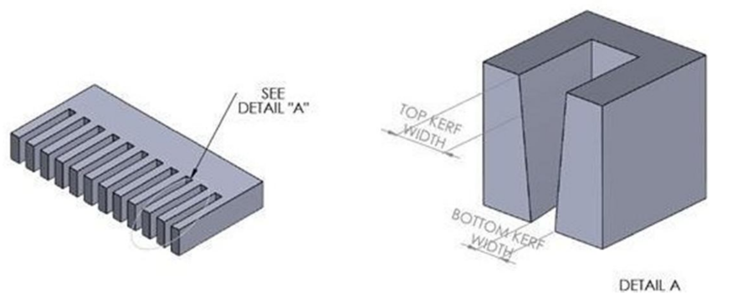


Fig.6 3D view of specimen

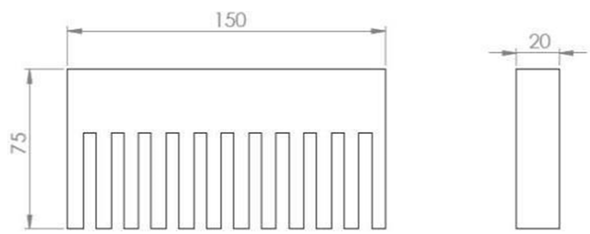


Fig.7 2D view of specimen

Taguchi uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Three parameters are considered as controlling factors. They are Nozzle traverse speed, Abrasive Flow rate, and Standoff distance, each parameter has three levels according to the Taguchi method, for three parameters and 3 levels L9 orthogonal array should be selected for experimentation. Table IV shows the design scheme of experiments.

TABLE IIIII
Chemical and Physical Properties of ms 2062

Sr. No	Elements	Abbreviation	Percentage	Sr. No	Property	Value
1	Carbon	C	0.167	10	Tensile strength	410 MPA
2	Manganese	Mn	0.71	11	Yield strength	240 MPA
3	Silicon	Si	0.198	12	Density	7850 kg/m^3
4	Nickel	Ni	0.058	13	Hardness	72 HRB(approximately 4 Moh)
5	Chromium	Cr	0.01			
6	Molybdenum	Mo	0.008			
7	Sulphur	S	0.022			
8	Phosphorus	P	0.017			
9	Carbon equivalent	CE	0.293			

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue XI Nov 2021- Available at www.ijraset.com

Table IVV
Level of Parameters used in Experiment

Input parameters	Level L1	L2	L3	Output parameters
NTS mm/min	40	50	60	Kerf Angle
AFR kg/min	250	300	350	MRR
SOD mm	2	3	4	Surface finish

Table V
Constant Parameters

Fixed parameter	Set value
Water pressure	380 MPa
Orifice diameter	0.36 mm
Nozzle length	101 mm
Nozzle Diameter	1.1 mm
Work piece thickness	20 mm
Work piece material	MS 2062
Abrasives	Garnet ,Brown fused alumina, Aluminum oxide
Abrasive size	80 mesh
Impact jet angle	90 degree

All machining procedures were done using a single pass cutting. For each cut, at least three measures were made and the average was taken as the final reading to minimize the error. The validation experiment was conducted using the optimum combination of machining parameters obtained, results were compared in Table VII, and errors were mentioned as tabulated in Table VI.

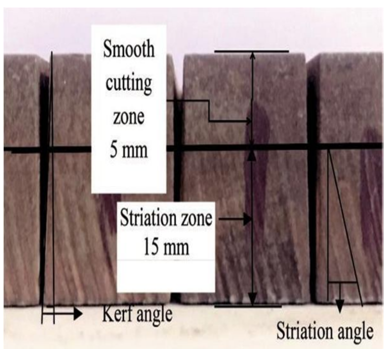
TABLE VI
Validation of Experiment

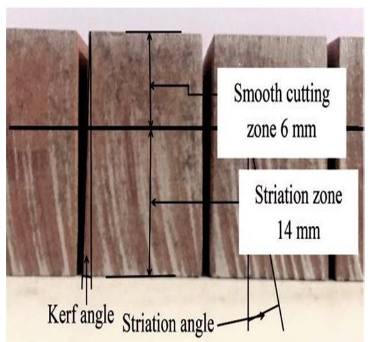
Optimum Parameters	Predicted optimum value using optimum setting (Using Garnet Abrasive)	Actual value produced and Error (Using Garnet Abrasive)	Predicted optimum value using optimum setting (Using Brown Fused Alumina)	Actual value produced and Error (Using Brown Fused Alumina)	Predicted optimum value using optimum setting (Using White Aluminium Oxide)	Actual value produced and Error (Using White Aluminium Oxide)
NTS 40mm/min AFR 350 kg/min SOD 4mm	Kerf angle: 1.11°	Kerf angle: 0.981° Error = 13.14%	Kerf angle: 0.792°	Kerf angle: 0.797° Error = 0.627%	Kerf angle: 0.670°	Kerf angle: 0.737° Error = 0.090%
NTS 60mm/min AFR 250kg/min SOD 4mm	MRR: 1282 mm^3/min	MRR: 1277.4mm^3/min Error = 0.360%	MRR: 1344 mm^3/min	MRR: 1565.4mm^3/min Error = 14.14%	MRR: 1401 mm^3/min	MRR: 1582.2mm^3/min Error = 11.45%

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue XI Nov 2021- Available at www.ijraset.com

Table VII
Results Obtained After with Different Abrasives

NTS (mm/min)	AFR (kg/min)	SOD (mm)	Kerf angle (Degree)	MRR (mm3/min)	Kerf angle (Degree)	MRR (mm3/min)	Kerf angle (Degree)	MRR (mm3/min)
			Garnet Abrasive		Brown Fused Alumina		White Aluminium Oxide	
40	250	2	1.316	819.6	0.846	995.6	1.079	1058.4
40	300	3	1.137	847.2	0.971	956.8	0.995	1011.2
40	350	4	0.981	856.4	0.865	996.8	0.737	1054.4
50	250	3	1.326	999	0.948	1186	1.264	1319.5
50	300	4	1.33	976.5	0.93	1181	1.155	1262.5
50	350	2	1.147	1017.5	1.071	1191	1.084	1296.5
60	250	4	1.187	1277.4	0.797	1565.4	1.297	1582.2
60	300	2	1.502	1104.6	0.85	1486.8	1.463	1565.4
60	350	3	1.39	1165.8	0.966	1457.4	1.3	1575.6





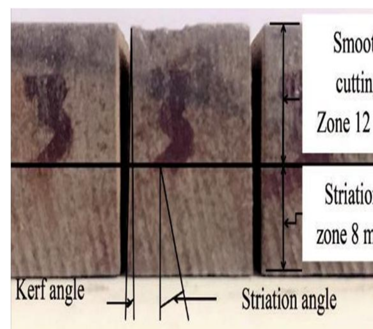


Fig.8 Kerf angle and striation angle of work piece using Garnet Fig.9 Kerf angle and striation angle of work piece using Brown fused alumina Fig.10 Kerf angle and striation angle of work piece using White aluminium oxide

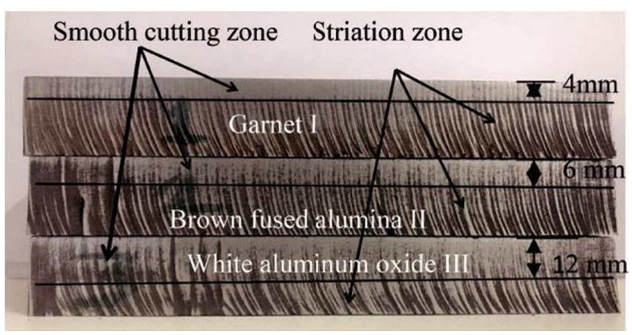


Fig.11 Comparative surface finish of work piece using abrasive I, II, III

VI. CONCLUSION

1) It is observed that we get a higher range of MRR in the case of White Aluminium Oxide, which is near to the ideal MRR of 1320 mm/min. If an average of MRR is taken, we get values for Abrasive III very near to ideal value (1320) but with concern to kerf angle Abrasive II near to ideal (0 degrees).
2) It is observed that the width of the smooth cutting zone of each workpiece,(4mm,6 mm, and 12 mm for Garnet, brown fused alumina, and white aluminium oxide respectively) a workpiece using white aluminium oxide shows the widest smooth cutting zone and lowest striation zone as compared with the other two workpieces (refer Figure 11).

3) The validation experiment was conducted using the optimum combination of machining parameters obtained and results were compared for each piece with very little error found.
4) It is observed that workpiece using White Aluminium Oxide) shows less Ra value, widest smooth cutting zone (refer to Figure 11), small striation angle (refer to Figure 10) as compared with the other two workpieces. It can be concluded that white aluminium oxide produces parts with a good surface finish, good MRR, less kerf angle as compared with Garnet hence White Aluminium Oxide can be used in place of Garnet, which is presently used by industry.

VII. ACKNOWLEDGMENT

I would like to thank my reporting manager and mentor for this project, Mr. Vipul Mamrawala, and my organization AM/NS India Limited, for providing me an opportunity and resources to do this research.

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