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Mathematical Model for Metal Removal in Abrasive Jet Drilling

[1]D.V.Srikanth, [2]Dr.M.SreenivasaRao
[1]*Department of Mechanical Engineering, St. Martin's Engineering College, Sec-bad, TS, India*
[2]*Department of Mechanical Engineering, JNTUH, Kukatpally, Hyderabad, TS, India*

Abstract: *In order to calculate material removal rate, formula have been developed from fundamentals .Since they are fundamentals they are more accurate than the theoretical formula being used by various authors. The result obtained by the proposed formula is compared with theoretical formula and is reported .Development of equations for material removal rate of AJM using fundamental principles.*
Abrasive jet machining is an advanced machining process and works based on mechanical energy. The metal removal takes place in AJM using high velocity abrasive particles mixed with a carrier gas (air) which imp rises on the work surface. This process works based on surface erosion process . The process parameters which controls the metal removal rate are air quality& pressure, Abrasive grain size, Nozzle material, nozzle diameter, Standoff distance between nozzle tip and work surface. The theoretical formulas developed by various authors are taken in to the account and developed a new practical formula for comparison and application for machined components. The new formula found successful and nearer to the theoretical formula. Hence forth the new developed formula for Metal removal rate can be used confidently.
Keywords: *Abrasive jet machine, material removal rate, Equabring, fundamentals.*

I. Introduction

AJM is useful [Butler, 1980; Dombrowski, 1983] in the manufacture of electronic devices, deburring, marking on electronic and other products, de flashing small castings, cutting titanium foil, and drilling glass wafers. This process is also used for engraving registration numbers on the toughened glass, frosting glass surfaces, and cutting thin sectioned fragile components. It however, pollutes the working environment.

Fig 1: Set up of AJM

An abrasive jet machining (AJM) system comprises the following sub-systems/elements: high pressure gas source, abrasive feeder, mixing chamber, nozzle, and abrasives. The high pressure gas, (air, nitrogen, or CO) is obtained either by a compressor or a cylinder to propel the abrasive particles to the mixing chamber. The gas should be dry and clean. In case of a compressor, air filter cum drier is used to avoid water/oil contamination with abrasive particles. The gas to be used should be *nontoxic, cheap*, and should have *low divergence*. It should be *easily available*. As air is free source and a compressor is sufficient to create the required pressure .it is pressurable as the operating fluid.

AJM nozzle is usually made of tungsten carbide or sapphire (usual life = 300 hr) with circular or rectangular cross-section. The nozzle material should have high resistance to wear. The nozzle pressure is generally maintained between 2-8.5 kg/cm^{2}depending upon the work piece material, desired accuracy, etc. Wear of the nozzle results in irregular and stray cutting and poor work accuracy. Stray cutting can be controlled by the use of masks made of soft materials like rubber (for less accurate works) or metals (for more accurate works). Mask is applied to cover that part of the job surface where machining is not required.

Aluminium oxide ($Al2O_3$), silicon carbide (Sic), glass boards, crushed glass, and sodium bicarbonate are some of the *abrasives* (size varies from 10 μ – 50 μ) used in AJM. Selection of abrasive depends upon the type of work material to be machined, desired material removal rate (MRR), and required machining accuracy. Al2o3 and silicon are good for cleaning, cutting, and debarring but for harder work materials other abrasives are selected. For obtaining matt finish, glass beads are good. Small abrasive particles are used for cleaning and polishing, while large particles perform better during cutting. The abrasive particles should have sharp and irregular shape, and should be fine enough to remain suspended in the carrier gas. Furthermore, the abrasives should be cheap. Reuse of the abrasives is not recommended because of two reasons: a) contaminated abrasives may block the nozzle passage, and b) whereas the cutting ability of used abrasive is much lower.

Important parameters that affect material removal rate in AJM are :**a)**Stand-Off-Distance (i.e., SOD, or sometimes called as nozzle-tip-distance, NTD),**b**) type and size of abrasive particles,**c**) flow rate of abrasive,**d**) gas pressure, **e**)type of work material, and **f**) feed rate. The effects of these parameters on process performance are discussed below.

Relationships between Stand-Off-Distance and volumetric material removal rate (MRR) as well as linear material removal rate (MRR). A change in the shape of the machined cavity with a change in SOD is observed in all processes . The range of SOD which usually varies from 0.75 to 1.0 mm,to obtain maximum medium . Low value of SOD improves accuracy, decreases kerf width, and reduces taper in the machined groove. However, light operations like cleaning, deburring , etc. are conducted with a large SOD (say, 12.5 - 75 mm).

AJM is a low material removal rate process (approx. 0.015 cm^3/min) and it can easily produce intricate details on hard and brittle materials. Production of narrow slots (0.12 - 0.25 mm), low tolerance (□ 0.12 mm), good surface finish (0.25 - 1.25 μ), and sharp radius (□ 0.2 mm) are some of the capabilities of the AJM process. AJM can machine without thermal damage to the work because the heat generation during machining is very small.

Previous studies [3, 4, 33, 34] showed that the erosion rate (mass removed from the surface by unit mass of impinging particles) depends on the type of materials and the impact angles. Ductile materials, such as mild steel, showed the greatest erosion rate at a shallow impact angle. On the other hand, more brittle materials such as glass and ceramics have rapid erosion rates when the particles were incident normal to the surface. The size of abrasive particles has also major effect on the erosion rate.

II. Methodology

The Mathematical formulae regularly used for finding the Metal Removal Rate in Abrasive Jet Machining are derived by various authors . These formulea are regularly used by researchers in the field.

Neema & Pandey (1977) proposed an equation for material removal rate by equating the kinetic energy of the particles impinging on to the work of deformation during indentation.

$$Q = k\, N\, d^3 v^{3/2} (\rho_{a/12\sigma y}) \qquad \text{\_\_\_\_\_\_\_\_\_\_} \quad (1)$$

Finnie (1960) showed that volume of Material(Q)eroded by impacting Particles of mass M carried in a stream of air can be calculated as

$$Q = Cf(\theta)\, M\, v^n \qquad \text{\_\_\_\_\_\_\_\_} \quad (2)$$

Where C& n are constants σ_s =Minimum flow stress of work material, ɵ is Impingement Angle.[6].

Sarkar & Pandey (1980) suggested a model to calculate MRR (Q) during AJM.

$$Q = x\, Zd^3 v^{3/2} (\rho/12H_{w)})^{3/4} \qquad \text{\_\_\_\_\_\_\_\_} \quad (3)$$

Where Z is no of particles impacting per unit time, D is mean diameter of Abrasive grain, P is the density, V is the velocity of abrasive particles, H_w is hardness of work material, X is a constant.[7].

A.El.Domity.et al.[3] Established a equation of MRR for brittle materials

$$MRR = \dot{m}_t = \frac{K_3\, \eta_a\, P^{1.25}\, D^2\, \rho^{0.5}}{\sigma_{fw}^{0.75}}; \quad mm^3/s$$

Domiaty et al highlighted that the velocity of the abrasive particles, which are carried by air, can be determined by applying Bernoulli equation at two points. The first point is inside the nozzle and the second is outside the nozzle. With some assumptions and formula simplifications, the velocity can be obtained as fellow;

$$v = \sqrt{\frac{2P}{\rho_{air+abrasive}}}$$

A New Formula have been developed and compared with the theoretical formulas regularly used.
Generally MRR is expressed in grams per second or mm3/sec. These units explain the quantity of material removed per second. The following steps give better idea about the new formula for MRR.
AJM is generally used for, cutting slot square or circular holes in the work piece. The dimension s of cut size and thickness of the material decide the volume of material removed. Whenever the process is performed, the time taken for the process is noted as 'z'. Then the MRR can be calculated as per the following table.

Table 1: Calculation of MRR based on type of cut

S.No	Type of cut	Dimensions of cut m cm	Formula Volume of M.R ^{cm3}	MRR volume basis $^{cm3/sec}$	MRR max basis gm/sec
1	Squqre	Side 'a' Thickness 't'	a^2*t	$a^2 t/4$	ρ $a^2 t/z$
2	Slot	Length 'l' Breadth 'b' Thickness 't'	L*b*t	L*b*t/z	ρ [l*b*t/z]
3	Circular	Diameter 'd' Thickness 't'	πd^2	$\frac{\pi d^2 t}{4z}$	$\frac{\rho[\pi d^2 t}{4z}]$
4	Rectangular with semi-circular end	Length 'L' Breadth 'b' Thickness 't'	πd^2	[lbt+$\pi b2$/4]/z	P[lbt+πb2/4]/z
5	Circular hole with keaf at top	Hole dia 'd' Keaf dia 'D' Thickness 't' ρ is density of material	$\frac{\pi d^2}{4} + \pi(D - d)3/6$	$\frac{\pi d^2}{4} + \pi(D - d)3/6$	ρ/z[$\frac{\pi d^2}{4} + \pi(D - d)3/6]$

The Experiments are conducted by taking Ceramic tile as specimen, Sic as abrasive. Experiments are conducted on the Test Rig which is designed and Fabricated at SMEC, Secunderabad. The abrasive Particles are mixed with air stream and directed towards work surface. The Abrasive flow rate was kept constant for the entire machining process. The jet nozzle was made of tungsten Carbide to carry high wear resistance. Several nozzles were manufactured with different bore diameters of 1 mm, 2 mm and 3 mm. Drilling of Ceramic sheets was conducted by setting the test rig on the parameters listed in Table 2.

Table 2: Parameters required for conducting drilling of Ceramic sheets

Medium	Air
Abrasive	Sic
Flow rate of abrasive	3 to 20 gram/min
Velocity	150 to 300 m/min
Pressure	2 to 8 kg/cm2
Nozzle size	1m to 3mm
Material of nozzle	Tongs tan carbide
Nozzle life	
Standoff distance	0.25 to 15 mm (8mmgenerally)
Work material	Non ceramic tile germanium, silicon etc
part application	Drilling

Abrasive density = 2.3 g/cm^3
Glass hardness (Hv) = 30
Glass fracture toughness =2.5 J/m^3
Glass stress flow (_few) = 5000 MPa

III. Experimentation & Results

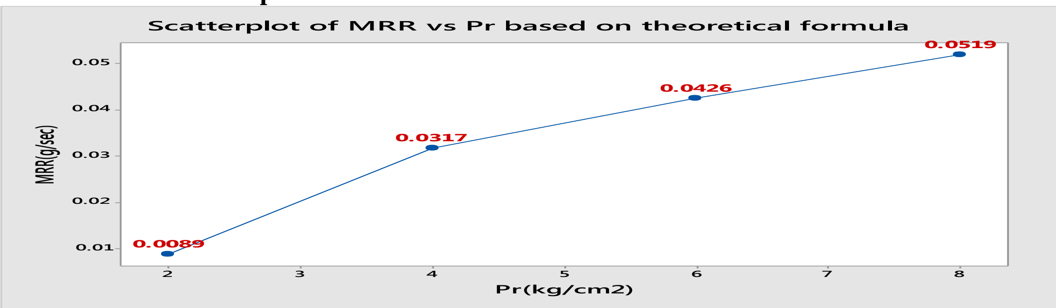
Experiments are conducted with the variation in Pressure, SOD, Nozzle Diameters by using the theoretical formulas which are derived by the previous researcher and validated the MRR values with the new mathematical approach.
Based on the Theoretical Formula the MRR can be Calculated as

$$MRR = \dot{m}_t = \frac{K_3\, \eta_a\, P^{1.25}\, D^2\, \rho^{0.5}}{\sigma_{fw}^{0.75}};\quad mm^3/s$$

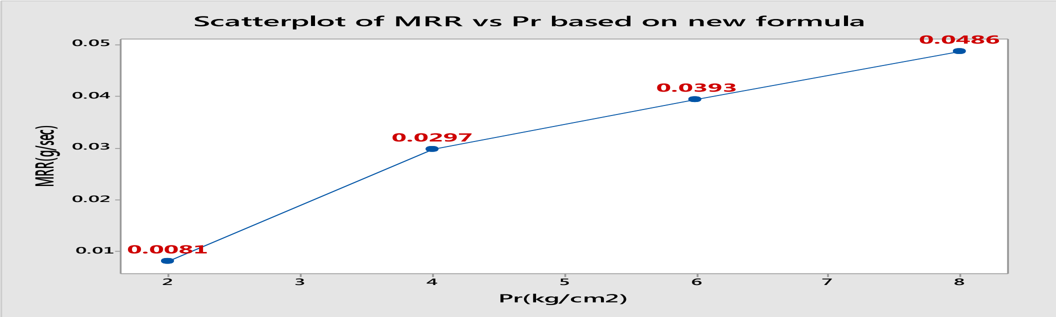
K_3 is constant and the value is 1.03
$\sigma_{fw}$is stress flow rate of the ceramics
ρ is the density of Abrasives 2.36 gm/cm^3
P is the Pressure of Air

By applying the above formula the Metal Removal rate attained was 0.0317 gm/sec .The same values are applied to the new formula of MRR which we derived. The MRR we got is 0.0297 gm/sec.The difference between theoretical results MRR is much nearer to the values obtained from fundamentals.The graphs on pressure vs MRR based on the Theoretical values and new formula values are analysed here.

Graph 1: MRR vs Pressure based on Theoretical Formula

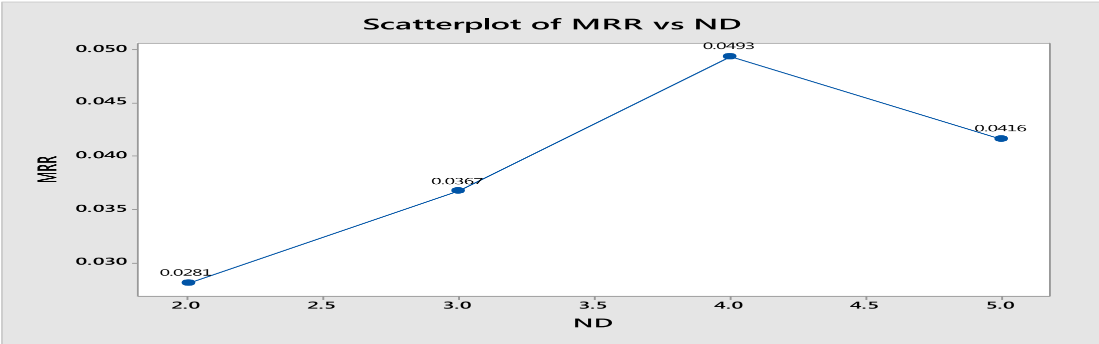


Graph 2: MRR vs Pressure based on Fundamental New Formula

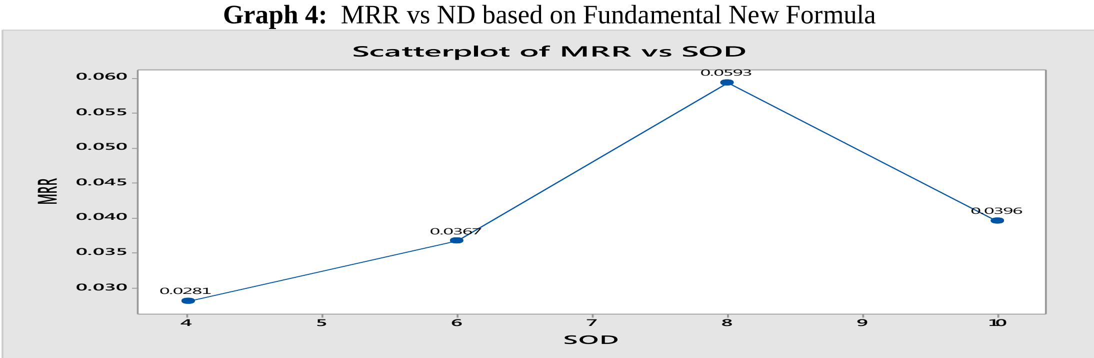


The following graphs highlight the effect of various parameters on metal removal rate and surface roughness. The factors used for the experimentation and for plotting graphs are pressure, nozzle diameter, stand-off distance and abrasive flow rate.By changing the pressure of air and keeping other parameters unchanged. It is observed that by increase in pressure the metal removal rate increases. It is also observed that by increase in nozzle diameter the metal removal rate increases but the surface roughness decreases.

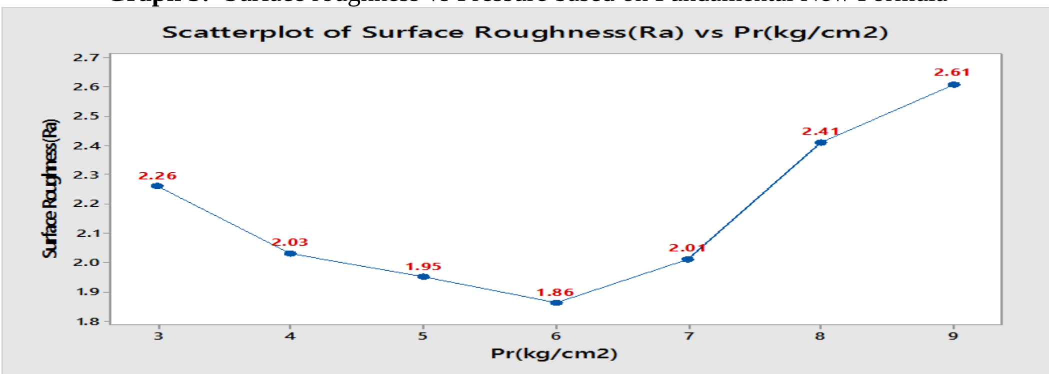
Graph 3: MRR vs ND based on Theoretical Formula



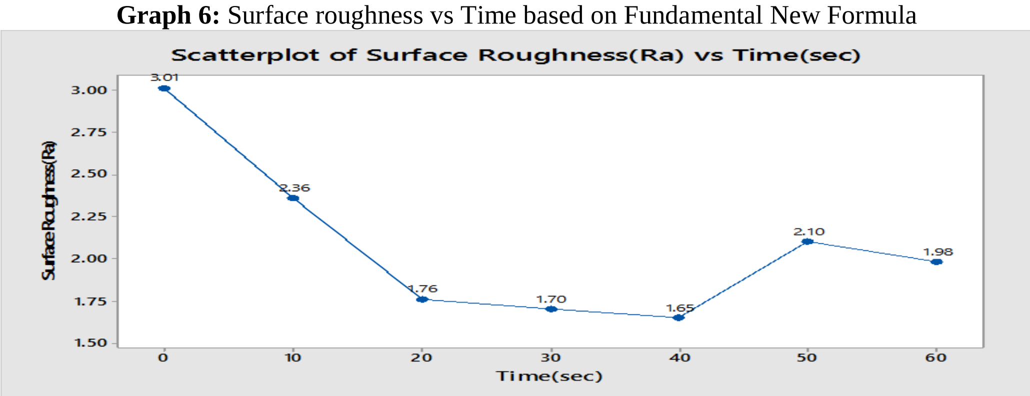
Graph 4: MRR vs ND based on Fundamental New Formula



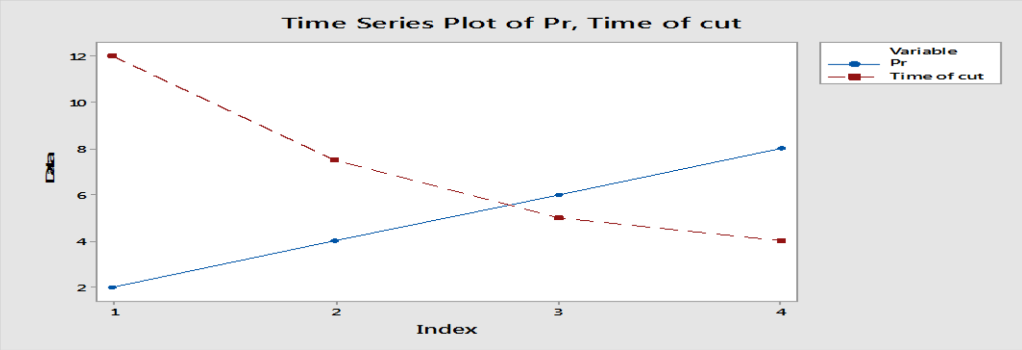
Graph 5: Surface roughness vs Pressure based on Fundamental New Formula



Graph 6: Surface roughness vs Time based on Fundamental New Formula

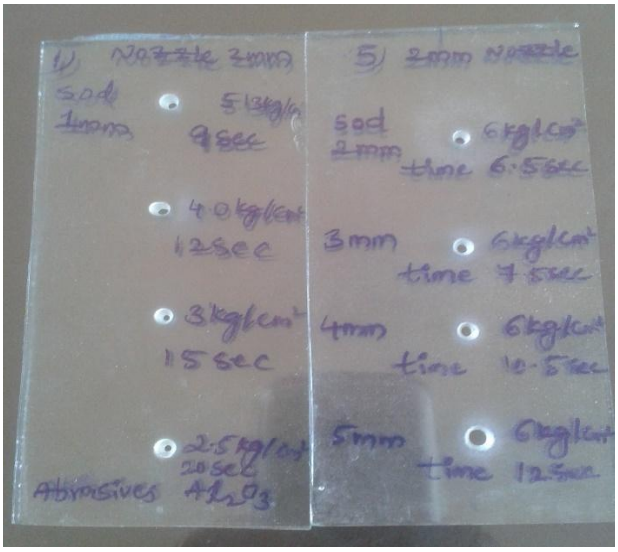


Graph 7: Pressure Vs Time of cut based on Fundamental New Formula



It is observed From Graph 1,2 that by increase in Pressure the Metal Removal Rate is also increased. Where from Graph 3,4,5, it is noted that by increase in SOD the Top and Bottom Surface diameters also increases. Graph6, 7 gives the relation between Pressure and Time, As the Pressure of Gas Increases the Cutting time will reduce. Graph 9,10 shows the relation between SOD and MRR, at optimised point Maximum MRR will be achieved, Later the MRR will decreases. Small metal removal rates at a low SOD is due to a reduction in nozzle pressure with decreasing distance, whereas a drop in material removal rate at large NTD is due to a reduction in the jet velocity with increasing distance. So we have to select a optimum value of NTD to get maximum material removal rate in AJM process.

It is also observed that by increase in Pressure the Metal Removal Rate is also increases. The results indicate that time decreases by increasing the Pressure. As the distance between the face of nozzle and the working surface of the work increases, the diameter of hole also increases because higher the nozzle tip distance allows the jet to expand before impingement which may increase vulnerability to external drag from the surrounding environment. It is desirable to have a lower nozzle tip distance which may produce a smoother surface due to increased kinetic energy. The compressed air from the compressor enters the mixing chamber partly prefilled with fine grain abrasive Particles. The vortex motion of the air created in the mixing chamber carries the abrasive particles to the nozzle through which it is directed on to the work piece. The nozzle and the work piece are enclosed in a working chamber with a Perspex sheet on one side for viewing the operation.

IV. Conclusions

The exact solution for MRR has been derived from fundamentals principles are accurate. MRR values calculated on the basis of theoretical equation is also plotted to show the variation in results. It can be concluded that the theoretical values based on the equation by Dimity at all is very near to the exact solution.

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