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Modeling and Experimental Investigation on Micro Abrasive Jet Machining

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***Abstract:*— Abrasive Jet Machining (AJM) is one of the high precision nonconventional mechanical machining processes in which material is removed by the impingement of high velocity stream of air and abrasives on to the work surface. The mechanics of material removal is mechanical erosion. The fractures of workpiece material in the form of small debris get carried away by the air from the cutting zone. This machining is well suited for brittle and ductile materials, where in brittle materials brittle fracture and for ductile materials shear fracture takes place. Most of the researchers are focused on machining of both the materials using developed/commercial setups. Less number of literatures concentrates on modeling concepts. An attempt has been carried out to develop a semi empirical model for material removal rate (MRR) on brittle material with AJM using dimensional technique. This is carried out by incorporating the various process parameters –pressure (P), stand of distance –SOD (S) and size of the particles (rp). The developed model was then validated with the experimental results.**

***Keywords:*----- Dimensional analysis, Material removal rate, Micro abrasive jet machining, Modeling.**

I. INTRODUCTION

Abrasive Jet Machining (AJM) is one of the upcoming efficient technologies for machining hard and brittle materials like ceramics, glass, semiconductor materials etc. Using conventional techniques it is quite difficult to machine hard materials since the cutting tool gets blunt and deformed resulting in poor surface finish on the work surface. This will generate large amount of heat which may affect the work material properties. Along with this, risk of cracks remaining in the work material leads to premature failure of work [1]. As a result, the productivity and accuracy will be reduced. AJM with high productivity opens a new way of precise machining that overcome the limitations caused by conventional machining. In AJM, the tools are fine abrasive particles which tend to remove material [2]. AJM has proven its capability in fabrication of wide varieties of micro features like micro accelerometer beam, capillary electrophoresis chips, micro mixer etc [3-5].

In AJM, removal of material takes place by the impact erosion through the action of concentrated high velocity stream of abrasives entrained in high velocity gas stream on the work material. The impact of the particle forms a brittle crack on the work surface which leads to impact erosion. The high velocity gas dislodges and removes the eroded particles. Many researchers have carried out theoretical as well as experimental studies to evaluate the response parameters - Material Removal Rate (MRR) and surface roughness with that of process parameters, air pressure, SOD, size of the abrasives, mass flow rate. But only a few of them carried out the semi empirical modeling concepts for AJM process. Using the dimensional analysis method [6], a mathematical model was developed for erosion rate for both hole and channel machining in glass. The model was represented as a function of particle impact parameters, target material properties and process parameters - air pressure, abrasive mass flow rate, SOD, machining time, and transverse speed. Similarly, [7] developed a model for predicting the depth of penetration when cutting an aluminium ceramics with and without nozzle oscillations. Here, parameters considered for modeling are nozzle transverse speed, SOD, pressure, size of the abrasive particles and material properties like hardness (H), modulus of elasticity (E), and material flow stress (σf). Dimensional analysis method is a feasible and more effective way to find the relation with large number of parameters.

Nomenclature $a, b, K, K_1, K_2, K_3, K_4, l, m, u, v, x, y$ are constants	
E	Young's modulus of the target material (GPa)
F	Force acting on the particle
H	Hardness of the target material (GPa)
p	Air pressure (N/mm^2)
r	Radius of hemispherical crater (mm)
s	Stand of distance (mm)
t	Machining time (min)
d_p	Particle diameter (mm)
m_a	Mass flow rate (g/min)
m_p	Mass of the abrasive particle (g)
N_i	Number of impact per time
r_p	Radius of the abrasive particle (mm)
v_p	Velocity of the particle(m/s)
v_r	Volume of material removed (mm)
δ_i	Depth of indentation (mm)
ρ_p	Density of the abrasive particle(g/mm^2)
σ_c	Compressive stress on work material(g/mm^2)

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In this paper, a semi empirical model for predicting MRR in AJM while machining holes on soda-lime glass has been developed using dimensional analysis technique. The obtained model is validated by comparing the model predictions with the experimental results.

II. MODEL FORMULATION

The material removal in AJM takes place due to the brittle fracture of the work material by a high velocity abrasive particles impacting on the surface. Fig.1. shows the interaction of abrasive particle with workpiece material. Modeling has been carried out with the following assumptions:

- Particle is of spherical shape
- Flow rate is assumed to be fixed for the model
- Machining time is taken as 1 min
- Volume of the material removed is in hemispherical shape
- Total kinetic energy of the particle is converted in to the
- work done to remove material

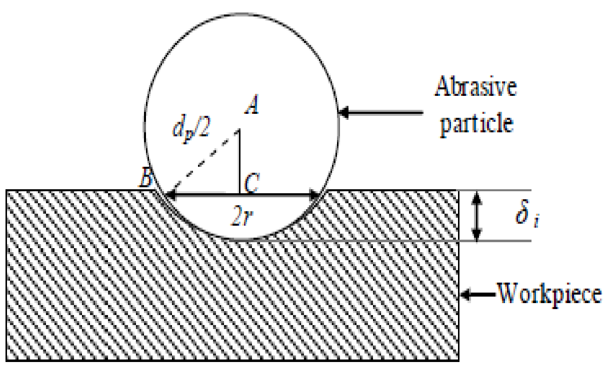

Fig.1. Interact ion of abrasive part icle with workpiece.

A. Material Removal Rate

From the geometry of indentation of abrasive particles on workpiece Consider ΔABC,

$$AB = \frac{d_p}{2}, \quad AC = \frac{d_p}{2} - \delta_i, \quad BC = r$$

Using Pythagoras theorem, from the right angle triangle ABC

$$\left(\frac{d_p}{2}\right)^2 = \left(\frac{d_p}{2} - \delta_i\right)^2 + r^2$$

$$r^2 = \left(d_p \times \delta_i\right) + \delta_i^2 \quad (1)$$

Here, the target material is glass which is a brittle material and its depth of indentation will not be more than 5% - 6% of its total height of the particle. In this case total height of the particle is its diameter (dp) whose three values are 0.045, 0.0575 and 0.07 mm. So 5% of the maximum value (0.07 mm) is 0.0035 mm. i.e., δi value is 0.0035, and the value of δi 2 is 0.00001225, which is very less and can be neglected. Therefore the Eq. (1) can be written as,

$$r = \sqrt{d_p \times \delta_i} \quad (2)$$

Volume of material removed is equal to the volume of the hemispherical impact crater that was produced by the single particle and it is given by,

$$V_r = \frac{2}{3}\pi\left(d_p \times \delta_i\right)^{3/2} \quad (3)$$

$$\text{Kinetic energy of the single particle} = \frac{1}{2} m_p \, v_p^2$$

$$KE = \frac{1}{2}\left(\frac{\pi}{6} d_p^3 \, \rho_p \, v_p^2\right) \quad (4)$$

From Eq. (4) Kinetic energy is a function of particle diameter (d_p), density of the particle (ρ_p), velocity of the particle (v_p). During the impact of abrasive particles, the work material would be subjected to maximum force *F*, which leads to an indentation of δ_i.

$$\text{Work done during indentation} = \frac{1}{2} \times \text{Force} \times \text{Indentation}$$

$$\text{Compressive stress}, \quad \sigma_c = \frac{\text{Force}}{\text{Area}}$$

Work done by the abrasive particles

$$= \frac{1}{2} \times \sigma_c \, \pi\left(d_p \, \delta_i\right) \times \delta_i \quad (5)$$

Assumed that the kinetic energy of the abrasive is fully used for material removal, and then the work done is equated to the kinetic energy, Work done by the particle = Kinetic energy of the particle

$$\frac{1}{2}\times\sigma_c\,\pi\left(d_p\,\delta_i\right)\times\delta_i = \frac{1}{2}\left(\frac{\pi}{6}\,d_p^3\rho_p v_p^2\right)$$

Solving the above equation the depth of indentation is given by,

$$\delta_i = v_p\,d_p\sqrt{\frac{\rho_p}{6\sigma_c}} \qquad (6)$$

In AJM, material removal takes place due to the erosion caused by the multiple impacts of particles. The overall effect of these multiple impacts can be obtained by direct multiplication of number of impact with volume of material removed by single particle impact. Therefore, the material removal rate can be expressed as the product of volume removed by a single particle and number of impacts per time (*Ni*). It depends on the mass flow rate, size of the particle and density of the particle. So it can be denoted as the ratio of mass flow rate of abrasive particles to the mass of abrasive particles.

$$N_i = \frac{m_a}{\frac{\pi}{6}\left(d_p\right)^3\rho_p} \qquad (7)$$

$$MRR = V_r \times N_i \qquad (8)$$

Substituting V_r from Eq. (3) and N_i from Eq. (7) into Eq. (8) where it gives as,

$$\text{MRR} = \frac{4\times\delta_i^{3/2}\,m_a}{\left(\sigma_c\right)^{3/2}\rho_p} \qquad (9)$$

Substituting the value of δi from Eq. (6) in Eq. (9)

$$MRR = \frac{\left(v_p\right)^{3/2} m_a}{\left(\sigma_c\right)^{3/4}\rho_p^{1/4}} \qquad (10)$$

Where vp and σc are unknown parameters and these can be represented as function of known parameters . Using dimensional analysis, corresponding equations for compressive stress (σc) and velocity of particle (vp) can be found out. The following section explains the systematic procedure.

B. Compressive stress

As the abrasive particles strike the workpiece with very high impact energy, the sharp tip of the particles move inside the work material resulting in the formation of plastic deformation zone under the indention tip due to compressive force and this plastic zone becomes larger as the compressive force increase [8]. The material removal takes place when both lateral crack and radial crack meets at the surface of the material which was produced by the particle impact. From Eq. (6), it is essential to find out the compressive stress σc. on the work material which is dependent on the particle and impacting parameters (rp, vp, ρp) as well as on the target material properties (E, H). Thus the compressive stress is a function of these parameters and it can be expressed as

$$\sigma_c = \phi\left(r_p, v_p, \rho_p, E, H\right) \qquad (11)$$

B.1 Dimensional analysis

Dimensional analysis technique determines a systematic arrangement of the variables in the physical relationship and combining dimensional variables to form non-dimensional parameters. According to the dimensional analysis technique all variables that appear in an equation can be assembled into a smaller number of independent dimensionless groups or products, in which it satisfies the condition that all the products must have the same dimension.

Dimensional analysis can be done either by Rayleigh method or by Buckingham -theorem. In this paper Buckingham -theorem is used instead of Rayleigh method. This is because in Rayleigh method only four numbers of variables can be taken otherwise if the variables are more the dimensional analysis will become complex and lengthy.

The Buckingham -theorem states that if there are *n* dimensional variables involved in a phenomenon, which can be completely described by *m* fundamental dimensions(such as mass, length, time etc), and are related by a dimensionally homogeneous equation, then the relationship among the *n* quantities can always be expressed in terms of exactly (*n*-*m*) dimensionless and independent terms[10].

The relations connecting the individual variables can be determined by an algebraic expression relating each dimensionless product. Following are the steps involved in this,

- If a problem involves ***n*** relevant variables ***m*** independent dimensions then it can be reduced to a

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relationship between ***n* – *m*** non-dimensional parameters, *1, 2 … n-m*.

- To construct these non-dimensional groups:

(i) Choose *m* dimensionally-distinct *repeating variables* (*Rv*).

(ii) For each of the $n-m$ remaining variables construct a non-dimensional π of the form

$\Pi = (Rv)_1^{a} (Rv)_2^{b} \ldots (Rv)_m^{c}$ (variable).

a, *b*, *c*, ... are chosen so as to make each π non-dimensional.

In order to ensure dimensional independence in {*MLT*} systems it is common but not obligatory to choose the repeating variables as a purely geometric quantity (e.g. length), a kinematic (time- but not mass-containing) quantity (e.g. velocity or acceleration) and a dynamic (mass - or force-containing) quantity (e.g. density).

The physical quantities involved in the Eq. (11) are *σc, vp, ρp, rp, E* and *H*.

The general form can be written as

$$f_1\left(\sigma_c, r_p, v_p, \rho_p, E, H\right) = K_1$$

Thus the total number of variables is 6 and all these variables are completely described by the three fundamental dimensions *M-L-T*. Hence *m* is equal to 3. Therefore there are (*n-m*) =3 dimensionless -terms, so that

$$f_2\left(\pi_1, \pi_2, \pi_3\right) = K_2 \tag{12}$$

In order to form these terms, 3 repeating variables are to be selected. Here *m* = 3 in such a way that they should contain all the three fundamental dimensions and they them self do not form a dimensionless parameter. Thus *rp*,(*L*), *vp* (*MT-1*), *ρp* (*ML-3*) as repeating variables, since the above mentioned requirements are fulfilled by these variables.

Physical quantities of dissimilar dimensions are expressed as product as follows,

$$\pi_1 = r_p^{a_1}\, v_p^{b_1}\, \rho_p^{c_1}\, \sigma_c$$

$$\pi_2 = r_p^{a_2}\, v_p^{b_2}\, \rho_p^{c_2}\, E$$

$$\pi_3 = r_p^{a_3}\, v_p^{b_3}\, \rho_p^{c_3}\, H$$

Expressing π_1 dimensionally in terms of *M-L-T* system

$$\pi_1 = M^0 L^0 T^0 = (L)^{a_1} \left(LT^{-1}\right)^{b_1} \left(ML^{-3}\right)^{c_1} \left(ML^{-1}T^{-2}\right)$$

Equating the exponents of *M, L* and *T*,

$M: 0 = c_1 + 1$

$L: 0 = a_1 + b_1 - 3c_1 - 1$

$T: 0 = -b_1 - 2$

From these equations,

$a_1 = 0;\ b_1 = -2;\ c_1 = -1$

Hence $$\pi_1 = \frac{\sigma_c}{\rho_p v_p^2} \tag{13}$$

Similarly by repeating the same procedure for finding the remaining π - terms

$$\pi_2 = \frac{E}{\rho_p v_p^2} \tag{14}$$

$$\pi_3 = \frac{H}{\rho_p v_p^2} \tag{15}$$

Substituting the Eqs. (13) – (15) in Eq. (12)

$$f\left(\frac{\sigma_c}{\rho_p v_p^2}, \frac{E}{\rho_p v_p^2}, \frac{H}{\rho_p v_p^2}\right) = K_2 \tag{16}$$

$$\frac{\sigma_c}{\rho_p v_p^2} = K_2 \left(\frac{E}{\rho_p v_p^2}\right)^a \left(\frac{H}{\rho_p v_p^2}\right)^b \tag{17}$$

The compressive stress, σ_c can be expressed as

$$\sigma_c = K_2\ \rho_p v_p^2 \left(\frac{E}{\rho_p v_p^2}\right)^a \left(\frac{H}{\rho_p v_p^2}\right)^b$$

Where K_2, *a, b* are coefficients and that can be determine through regression analysis

$$MRR = \frac{(v_p)^{3/2}\, m_a}{\left(K_2\, \rho_p v_p^2 \left(\frac{E}{\rho_p v_p^2}\right)^a \left(\frac{H}{\rho_p v_p^2}\right)^b\right)^{3/4} \rho_p^{1/4}} \tag{18}$$

Rearranging the Eq. (18)

$$MRR = K_3 \frac{m_a}{\rho_p} \left(\frac{\rho_p}{E}\right)^u \left(\frac{\rho_p}{H}\right)^v v_p^{2(u+v)} \tag{19}$$

Where $K_3 = 1/K_2^{3/4}$, $u = 3a/4$, $v = 3b/4$ are constants.

C. Velocity of the particle

Before implementing Eq. (19), it is necessary to find out the velocity of the particle. To understand the particle erosion process in AJM, particle velocity is one of the important jet characteristics. The kinetic energy plays a crucial role in plastic deformation and crack generation during the erosion process. Thus, material removal rate is strongly dependent on the velocity of the particle [9]. Finding the accurate value for velocity in a theoretical manner is very complicated and time consuming because of collision between the particles and particles with nozzle wall. So the velocity can be expressed as a function of five parameters in which it depend on. They are the radius of the particle *(rp)*, air pressure (*P*), stand of distance (*S*), mass flow rate (*ma*), machining time (*t*).

$$v_p = f\left(P, S, \rho_p, t, r_p\right) \qquad (20)$$

Here three repeating variables are selected in such a way that they should contain all the three fundamental dimensions and they them self do not form a dimensionless parameter are. They are P ($ML^{-1}T^{-2}$), ρ_p (ML^{-3}), and t (T).

The physical quantities of dissimilar dimensions are expressed as product as follows,

$$\pi_1 = P^{a_1}\,\rho_p^{b_1}\,t^{c_1}\,v_p$$

$$\pi_2 = P^{a_2}\,\rho_p^{b_2}\,t^{c_2}\,S$$

$$\pi_3 = P^{a_3}\,\rho_p^{b_3}\,t^{c_3}\,r_p$$

Expressing π_1 dimensionally in terms of *M-L-T* system

$$\pi_1 = M^0L^0T^0 = \left(ML^{-1}T^{-2}\right)^a\left(ML^{-3}\right)^b\left(T\right)^c\left(LT^{-1}\right)$$

Equating the exponents of *M, L* and *T*,

$M: 0 = a_1 + b_1$

$L: 0 = -a_1 - 3b + 1$

$T: 0 = -2a_1 + c_1 = 1$

From these equations,

$a_1 = -1/2;\ b_1 = 1/2;\ c_1 = 0$

Hence $\pi_1 = v_p\sqrt{\frac{\rho_p}{P}}$ (21)

Similarly same procedure is carried out for finding $\pi_2\,\pi_3$ terms

$$\pi_2 = \frac{S}{t}\sqrt{\frac{\rho_p}{P}} \qquad (22)$$

$$\pi_3 = \frac{r_p}{t}\sqrt{\frac{\rho_p}{P}} \qquad (23)$$

The functional relationship between the three π terms can be written as

$$\pi_1 = f\left(\pi_2, \pi_3\right)$$

$$v_p\sqrt{\frac{\rho_p}{P}} = K_4\left(\frac{S}{t}\sqrt{\frac{\rho_p}{P}}\right)^x\left(\frac{r_p}{t}\sqrt{\frac{\rho_p}{P}}\right)^y$$

The velocity of the particle

$$v_p = K_4\sqrt{\frac{P}{\rho_p}}\left(\frac{S}{t}\sqrt{\frac{\rho_p}{P}}\right)^x\left(\frac{r_p}{t}\sqrt{\frac{\rho_p}{P}}\right)^y \qquad (24)$$

Where K_4, x and y are coefficients that can be found out through regression analysis.

Substituting the Eq. (24) in Eq. (19)

$$MRR = K_3\frac{m_a}{\rho_p}\left(\frac{\rho_p}{E}\right)^u\left(\frac{\rho_p}{H}\right)^v\left(K_4\sqrt{\frac{P}{\rho_p}}\left(\frac{S}{t}\sqrt{\frac{\rho_p}{P}}\right)^x\left(\frac{r_p}{t}\sqrt{\frac{\rho_p}{P}}\right)^y\right)^{2(u+v)}$$

Where K_4, x and y are coefficients that can be found out through regression analysis.

Substituting the Eq. (24) in Eq. (19)

$$MRR = K_3\frac{m_a}{\rho_p}\left(\frac{\rho_p}{E}\right)^u\left(\frac{\rho_p}{H}\right)^v\left(K_4\sqrt{\frac{P}{\rho_p}}\left(\frac{S}{t}\sqrt{\frac{\rho_p}{P}}\right)^x\left(\frac{r_p}{t}\sqrt{\frac{\rho_p}{P}}\right)^y\right)^{2(u+v)}$$

Rearranging the above Equation,

$$MRR = K\frac{m_a}{\rho_p}\left(\frac{P}{E}\right)^u\left(\frac{P}{H}\right)^v\left(\frac{S}{t}\sqrt{\frac{\rho_p}{P}}\right)^l\left(\frac{r_p}{t}\sqrt{\frac{\rho_p}{P}}\right)^m \qquad (25)$$

Here $K=K_3 \cdot K_4^{2(u+v)}$; $l=2x(u+v)$; $m=2y(u+v)$ are constants that can be determined through regression analysis.

III. EXPERIMENTAL PROCEDURE

Experiments have been carried out to understand the influence of process parameters on material removal rate in AJM and to find out the coefficients in the semi-empirical model which was developed for hole. The experiments were carried out on a laboratory-built machine, in which air is selected as the carrier gas. Soda lime glass was used as the work material whose properties are summarized in Table I. The abrasive particles selected for machining is Aluminium Oxide (Al2O3) having a density of

3.95 g/cm3 and a size of 0.045 mm, 0.0517 mm and 0.07 mm were used.

Table I. Material properties of Soda lime glass

Elastic modulus E (GPa)	70
Hardness H (GPa)	5.5
Density ρ_t (g/cm^3)	2.5

In AJM process more number of parameters will affect the cutting action. But in the current work, only important and easy to control variables were considered. Thus , the material removal rate was studied under five major process parameters which include air pressure, SOD, machining time, density and size of the abrasive particles. The ranges of the parameters used in this experiment were selected based on the system limitation and it is given in Table II. In order to get the experimental data for judicious analysis within the least number of tests, the Taguchi orthogonal array, design of experiment (DOE) procedure was used to design the experiments. Since there are three factors and three levels, L9 orthogonal array experimental design is used which gives the various combinations of parameters. Each work material was cleaned and weighed prior to and after each experiment using a Mettler Toledo digital balance.

Table II. AJM process parameters while machining Soda-lime glass

Process parameters	Level 1	Level 2	Level 3
Air Pressure P (N/mm^2)	0.5	0.7	0.9
Stand of Distance S (mm)	1	2	3
Abrasive Size d_p (mm)	0.045	0.07	0.0575

IV. MODEL ASSESSMENT

The model in Eq. (25) can be considered as the material removal rate model for brittle materials particularly for various glasses. The constants in the model were found out from experiments. Based on the data that was obtained from experiments, a regression analysis has been carried out using MATLAB software. While carrying out the regression analysis, E, H, ρp , ma and t are kept constant. The final MRR model for machining holes on soda lime glass is given by

$$MRR = K\frac{m_a}{\rho_p}\left(\frac{P}{E}\right)^{-1.0216}\left(\frac{P}{H}\right)^{1.9021}\left(\frac{S}{t}\sqrt{\frac{\rho_p}{P}}\right)^{0.6844}\left(\frac{r_p}{t}\sqrt{\frac{\rho_p}{P}}\right)^{-0.5313}$$

Rearranging the equation gives

$$MRR = 8.603\frac{m_a P^{0.8039} S^{0.6844} E^{1.0216}}{\rho_p^{0.9347} r_p^{0.5313} t^{0.1531} H^{1.9021}} \qquad (27)$$

The above equation is valid for the conditions specified in the experiments. In this equation, rp is in µm, S in mm, P is in N/mm2, E and H are in GPa, ρp is in g/cm3, ma is in g/s and t is in s. As per the semi- empirical model, the MRR is proportional to the mass flow rate, air pressure, SOD, and inversely proportional to particle density and size, machining time and work material hardness.

V. RESULTS AND DISCUSSION

A semi-empirical model of material removal rate of soda- lime glass has been formulated with parameters involving pressure, SOD and properties of both abrasive particles and work material. From the experimental result, the value for the coefficients and power index in Eq. (25) was calculated for each workpiece by employing the regression analysis. The verification of the coefficients and power index of the given Eq. (27) shows encouraging results. A further comparison of predicted values with experimental results based on the model for MRR has been carried out. The prediction error is calculated based on the formula.

$$Error(\%) = \left|\frac{Predicted\ result - Experimental\ value}{Experimental\ result}\right| \times 100$$

Here, the prediction of MRR of work material is showing a reasonable agreement with the experimental results. Table III display the comparison between the experimental data and predicted values that was obtained from the semi empirical model.

A significant assessment was also made based on the percentage deviation of predicted model with respect to the experimental values.

Total number of experiments (N) = 9

Average error (μ) =

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Total number of experiments $(N) = 9$

Average error $(\mu) =$

$$\frac{(12.4+19.7+36+17.7+12+14.8+11.6+51.2+2.7)}{9} = 19.7\%$$

$$\text{Standard deviation} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \mu)^2} = 14\%$$

$$\text{Average deviation} = \frac{\sum |X_i - \mu|}{N} = 10.5\%$$

Here, the average deviation for MRR in hole machining of soda lime glass is 10.5% with a standard deviation of 14%.

Table III. Comparison of experimental data with model prediction of MRR on work

Sl No.	Conditions			Material Removal Rate			Error %
	Pressure P (N/mm²)	SOD S (mm)	Size of the Particles r_p (mm)	Experimental MRR (mg/s)	Predicted MRR (mg/s)	Differences	
1	0.5	1	0.45	0.0517	0.0453	0.0064	12.4
2	0.5	2	0.07	0.0717	0.0575	0.0141	19.7
3	0.5	3	0.0575	0.1317	0.0843	0.0474	36.0
4	0.7	1	0.0575	0.0633	0.0521	0.0112	17.7
5	0.7	2	0.045	0.1083	0.0954	0.0130	12.0
6	0.7	3	0.07	0.0867	0.0995	0.0129	14.8
7	0.9	1	0.07	0.0650	0.0574	0.0076	11.6
8	0.9	2	0.0575	0.2100	0.1025	0.1075	51.2
9	0.9	3	0.045	0.1583	0.1541	0.0043	2.7

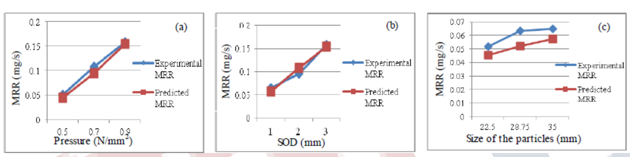

Fig.2. Predicted and experimental results for material removal rate of hole machining in soda -lime glass.

Fig.2. illustrates the predicted and experimental data for MRR of hole machining in soda- lime glass. It can be seen from Fig. 2 (a) and 2. (b) that MRR increases with increase in air pressure and SOD respectively. These trends can be interpreted as, when the pressure increases the particle velocity increase resulting in MRR. Similarly, at small SOD, the MRR increases and later it decreases due to the inertia effect of suspended particles. SOD with MRR shows a linear trend which reflects that as SOD increase the contact diameter as well as the particle velocity increases resulting in the increase of MRR. Fig.2 (c) shows the relation between sizes of the particles with that of MRR. It explains that as size of the particle increases (coarse particles); although it attains low velocity, the contact diameter at the impact zone on the workpiece material is large resulting in high removal rate. Whereas in fine particle though the velocity is high, the removal rate is low due to the small contact diameter of particle at the impact zone.

VI. CONCLUSIONS

A semi empirical model for MRR in machining holes on soda lime glass by AJM has been formulated using the dimensional analysis technique. Properties of abrasive particles, target material and important process parameters that affect the material removal rate were considered. A regression analysis has been carried out from the data which was generated by the DOE procedure. It has been seen from the model that the mass flow rate, size of the abrasive particles, SOD and pressure have positive exponent. A comparative study was made between the experimental data and predicted results. From this, the developed model provided favorable results with that of the experimental data with an average deviation of 10.5%.

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