Abrasive jet machining of glass: Experimental investigation with artificial neural network modelling and genetic algorithm optimisation

El Shimaa Abdelnasser1, Ahmed Elkaseer1,2* and Ahmed Nassef1

Abstract: The paper presents an experimental-based study of abrasive jet machining (AJM) considering the effect of changing process parameters. A series of drilling tests were carried out on glass workpieces using sand as the abrasive powder. The influence of each process parameter; applied air pressure, standoff distance, nozzle diameter, particle grain size and impact angle on the machining performance was determined in terms of the resultant material removal rate (MRR). The experimental results revealed that MRR was highly dependent on the kinetic energy of the abrasive particles, with the applied pressure the dominant parameter. The experimental results were compared with an erosion rate model previously published by Jafar et al. Though correct trends were predicted, there was a large discrepancy between model and measured values. An artificial neural network (ANN) was utilised to model the MRR more precisely, particularly to establish relationships between applied machining parameters and experimentally measured MRR and achieved a maximum error of only 5.3%. A Genetic Algorithm (GA) was applied to optimise the model and identify the conditions to maximise the MRR. The results were experimentally validated and good agreement found between the experimental results obtained and the ANN and GA predictions.

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PUBLIC INTEREST STATEMENT

Abrasive jet machining (AJM) is an effective method of machining hard and brittle materials such as glass and ceramics which are difficult to shape with conventional processes. In AJM a focused stream of fine abrasive particles carried by highly pressurised air strikes the workpiece and material is removed from the surface by mechanical erosion. The air stream carries both the abrasive particles and the fractured material away. In addition to its wide applications at the macro-scale, AJM is playing an increasingly significant role in micro-machining, especially cutting such features as micro-channels and micro-holes for the manufacture of micro-electronic devices. AJM is highly flexible because the air and abrasive can be carried by hoses to almost any part of the workpiece, and cost effective because of the low cost of the equipment required and the smooth surface finish obtained. This research will help extend the use of the AJM process to both new and traditional industrial processes.
Subjects: Artificial Intelligence; Industrial Engineering & Manufacturing; Manufacturing Engineering; Production Engineering

Keywords: abrasive jet machining; artificial neural network; genetic algorithm; material removal rate; optimisation

1. Introduction
In abrasive jet machining (AJM), a focused stream of fine abrasive particles carried by highly pressurised air strikes the workpiece, and material is removed from the surface by mechanical erosion. High pressure air (or gas) gives the particles a high velocity (high kinetic energy) as they leave the nozzle to impact the workpiece and cause small fractures. The air stream carries both the abrasive particles and the fractured material away (Indian Institute of Technology, Kharagpur, 2015; Jagadeesha, 2015; Marinov, 2012).

AJM is an effective machining method for hard and brittle materials. Moreover, in addition to its wide applications at the macro-scale, it has recently played a significant role in micro-machining, especially micro-sized features such as micro-channels and micro-holes in the manufacture of micro-devices. For a highly efficient AJM process, it is necessary to optimise the process parameters to increase the material removal rate (MRR) while obtaining a generated surface of good quality (Jafar, Spelt, & Papini, 2013).

The artificial neural network (ANN) is a modelling technique to determine relationships between input/output parameters based on experimental data (Maros, 2012). The ANN is composed of interconnected neurons working in parallel, and is usually used to solve a specific problem (Abdel-Naby, 2014; Maros, 2012). An ANN has the ability to learn by example which makes it a very flexible and powerful tool. A particularly attractive feature is that it can improve its own rules, so that the more decisions it makes, the better the decision-making becomes (Yadav, Yadav, & Jain, 2013). Neural networks are structured in layers composed of a number of interrelated ‘nodes’. An input layer interconnects with one or more hidden layers where the actual processing is undertaken by a system of weighted connections. The hidden layers then communicate with an output layer where the answer is output (Abdel-Naby, 2014). This allows optimisation of the process being studied and can identify best possible performance. There are a large number of optimisation techniques. The genetic algorithm (GA) is an optimisation algorithm and is especially useful with those problems where the objective function is discontinuous, non-differentiable, stochastic and/or nonlinear (Sharma, Naik, & Patel, 2015; Stephen & Ajay, 2013). GAs have been widely used in a variety of applications such as automatic programming and machine learning (Sharma et al., 2015).

Following this introduction, the paper presents and discusses previous related work. Then it describes the test rig used during the investigation and the design of the experiments, followed by a discussion of the experimental results obtained and compares these results with the previously developed by Jafar et al. (2013). After that, the paper introduces the implementation of the ANN followed by the GA optimisation technique followed by an experimental trial to validate the result. Finally, conclusions are drawn.

2. Related work
A considerable number of investigations have been carried out on AJM both to explain the various erosion mechanisms and to study the factors influencing performance; MRR, dimensional accuracy, obtainable surface quality, etc.

The brittle and ductile erosion modes have been described frequently in the literature. In brittle fracture, the material removal occurs due to the formation and propagation of cracks in the workpiece material (Aquaro & Fontani, 2001; Lawn & Marshall, 1984; Leonard, 2003). When the particles
impact the workpiece with sufficient force, the contact area is plastically deformed. Large tensile stresses are generated in the target material that result in radial and lateral crack formation (Aquaro, 2010; Bouten, Scholten, & Pourreux, 1999; Chen, Hutchinson, & Evans, 2005; Gross, Price, & Glaesemann, 2013; Marshall, Lawn, & Evans, 1982; Wensink, 2002; Wensink, Berenschot, Jansen, & Elwenspoek, 2000). Material removal takes place when the lateral crack reaches the surface as shown in Figure 1 (Wensink, 2002). The volume of cracks depends mainly on the mechanical properties of the target material and the kinetic energy of the particles (Aquaro, 2010; Bouten et al., 1999; Chen et al., 2005). Maximum erosion for brittle materials occurs at a 90° impact angle, i.e. the beam is perpendicular to the work surface.

With ductile erosion, material removal takes place by plastic deformation due to shearing stresses. Ductile materials show maximum erosion rate at a small impact angles of 15°–30° where the particles sweep the surface and leave with some residual kinetic energy (Neilson & Gilchrist, 1986; Sundararajan & Roy, 1997; Wensink & Elwenspoek, 2002). However, at higher impact angles the particles can come to rest in the surface during the cutting process (Adler, 2002; Finnie, 1972; Neilson & Gilchrist, 1986; Sundararajan & Roy, 1997).

The effects of process parameters on the impact erosion rate when using solid particles have been major topics of research in recent years. Sundararajan and Roy (1997) investigated the effects of particle shape on the erosion rate. It was found that at small impact angles, particles with more angular surfaces caused higher erosion rates than particles with more rounded surfaces. Desale, Gandhi, and Jain (2005) reported that increase in density, hardness and angularity of the impact particles caused increased wear. Desale, Jain, and Gandhi (2009) and other research groups (Liebhard & Levy, 1991; Lynn, Wong, & Hector, 1991; Ran et al., 2014) have reported that increasing particle size leads to larger and deeper indentations and higher erosion rates.

Hutchings (1981) conducted an experimental investigation of AJM, measuring erosion rate for both ductile and brittle materials for different particle velocities. It was found that, all other factors being equal, erosion rate increased with increased particle velocity. Jagadeesha (2015) reported that increasing the standoff distance (SoD) leads to an increase in erosion up to a certain value, after which, the erosion rate decreases again. This is attributed mainly to the effect SoD has on the impact velocity of particles and their associated kinetic energy. Wakuuda, Yamauchi, and Kanzaki (2002) investigated the effect of properties of the workpiece and abrasive powder when machining ceramic materials using AJM. It was found that MRR was affected by fracture toughness and hardness of the target material, and significantly influenced by the type of abrasive powder used.
A number of experimental studies on the machining of glass by AJM have been reported (Chandra, 2011; El-Domiaty, Abd El-Hafez, & Shaker, 2009; Fan, Wang, & Wang, 2009; Grover, Kumar, & Murtaza, 2014; Kandpal, Kumar, Kumar, Sharma, & Deswal, 2011; Padhy & Nayak, 2014; Sharma & Deol, 2014; Vadgama, Gaikwad, Upadhyay, & Gohil, 2015; Zhang, Kuriyagawa, Yasutomi, & Zhao, 2005). El-Domiaty, et al. (2009) studied this problem by conducting a series of drilling experiments using sand as the abrasive material with different values for other process parameters. They found that the MRR increased with increase in particle size, applied pressure ($P_r$) and nozzle diameter ($d_n$). Chandra (2011) and Kandpal et al. (2011) also carried out test drilling of glass by AJM. Their results showed that as $P_r$ increased the MRR increased. Vadgama et al. (2015) and Padhy and Nayak (2014) used the Taguchi method to design experiments for drilling glass by AJM. They also found that MRR increased with the increase of both $P_r$ and SoD up to a certain limit after which there was a decrease of MRR. Sharma and Deol (2014) found that the taper cut and overcut of holes decreased with increasing $P_r$ and $d_n$, and decreasing SoD. Grover et al. (2014) combined the Taguchi method and ANOVA to analyse the effect of process parameters on AJM and found that MRR decreased with decreasing impact angle and abrasive particle grain size ($d_g$). Fan et al. (2009) developed predictive mathematical models for the MRR in the micro-machining of holes and channels on glasses using AJM. It was found that the MRR increased with the increase in $P_r$, SoD and slightly decreased with the increase in abrasive mass flow rate. Zhang et al. (2005) investigated micro abrasive intermittent jet machining for drilling small holes. This technique was used to ensure the regular removal of the abrasive particles and so prevent system blockages.

A review of the literature shows that the great majority of published work is experimental. There exists a serious lack of research in the area optimisation, and this study addressed this gap, in particular to optimise the AJM process. In this context, this study included a systematic study to investigate the influence of the process parameters on the AJM and thus control them for the best possible performance. The experimental trials were carried out under a range of $P_r$, SoD, $d_n$, and $d_g$. After that, the results were compared with the MRR model published recently by Jafar et al. (2013). Based on the experimental results a model for the MRR was produced using an ANN. Finally, a GA was used to optimise the process parameters for maximum value of MRR, using the best structure developed by the ANN as a fitness function.

3. Experimental investigation

3.1. Machining setup

In order to carry out the experimental work, a CNC machine with three axis capability was adapted to enable the fixing of the AJM tool. The machine has a work-table with the following dimensions 150 × 250 × 25 cm in the $x$-, $y$- and $z$-axes, respectively, with a maximum traverse speed of 120 m/min.

A compressor with a maximum pressure of 10 bar was used to achieve a range of $P_r$. Three cylindrical tubes each of length 30 mm and internal diameters 4.0, 5.0 and 6.0 mm were used as the nozzles for the cutting process, see Figure 2. Sand was chosen as the abrasive material. In order to prepare the sand for the experiment, it was dried and sieved to separate the grains into different sizes. For abrasive sieving, a sieve shaker, with seven sieves was used to obtain three ranges of particle sizes, see Figure 3. The average diameter of the sieved particles in each of the three ranges used in the experimental work were 150 ± 50, 300 ± 50 and 600 ± 50 μm.

Soda lime glass of 3.0 mm thickness was selected as a target. Using the adjustment holder shown in Figure 4, the blasting gun could be tilted to give suitable impact angles. Figure 5 illustrates the layout of the AJM equipment.

The properties of abrasive (sand) and the workpiece (glass) are as follows (GWP Consultants, 2010); Density of abrasive ($\rho_p$) = 2.3 g/cm$^3$, Glass hardness ($H$) = 5.5 GPa, Glass fracture toughness ($K_c$) = 0.76 MPa√m, Glass elastic modulus ($E$) = 72 GPa, Glass density ($\rho_t$) = 2.5 g/cm$^3$. 
Figure 2. The three nozzles used in the tests, all dimensions in mm.

Figure 3. Sieve shaker used to separate sand grains according to diameter.
3.2. Process parameters

Four parameters were varied to assess their influence on MRR: $P$, SoD, $d_r$, and $d_g$. Each parameter was tested at three values, see Table 1.

Initial experiments were conducted at an impact angle of 90°. Subsequent tests were carried out at impact angles of 70° and 50° to estimate the effect of impact angle on machining performance. However, it is worth emphasising that prior to commencing the tests, the mass flow rate was measured experimentally at each set of values of the applied process parameters.
3.3. MRR evaluation

MRR can be evaluated by Equation (1); where the weight loss over the test period is divided by the time of the test in minutes.

\[
MRR = \frac{(w_b - w_a)}{t} \quad \text{(g/min)}
\]  

(1)

where \(w_b\) is the mass of workpiece before the process began, \(w_a\) is the mass of workpiece after the process ended, and \(t\) is the machining time in minutes. The machining time for each trial was the time taken to obtain a hole completely through the test piece. This, of course, varied depending on the given cutting conditions. Each experiment was carried out three times and average value was calculated and presented as the result.

4. Results and discussion

Figure 6, shows test specimens after the drilling process, carried out under different process conditions.

4.1. Effect of process parameters on abrasive mass flow rate

Figure 7(a) and (b) illustrates the relationship between process parameters \(P, d_g, d_n\) and the obtained mass flow rate of the sand particles. The results demonstrated that mass flow rate increased with the increase in \(d_n\) at constant pressure, because the larger nozzle diameter allows a higher number of particles to exit in a given time. However, when \(d_g\) becomes relatively large with respect to \(d_n\), the interaction between the particles as they pass through the nozzle becomes
significant and this interaction generates an effective frictional force which reduced the mass flow rate. For example, it was observed that at minimum $d_n$ the larger the particle diameter (of those available here) the lower the mass flow rate, see Figure 7(a). At $d_n = 5.0$ mm, the highest mass flow rate was observed with $d_g = 300$ μm. For maximum nozzle diameter, $d_n = 6.0$ mm, the relative values of $d_g$ and $d_n$ was such that maximum abrasive flow was obtained using a grain of size of $600$ μm and minimum abrasive flow occurred with grain size of $150$ μm. It appears that the maximum abrasive mass flow rate for the different particle sizes is associated with using the appropriate $d_n$.

It was found that $P_r$ was the most significant parameter influencing the abrasive mass flow rate with mass flow rate increasing monotonically with $P_r$. Higher pressure generated higher particle velocity from the nozzle and thus increased the overall mass flow rate.

4.2. Effect of process parameters on the MRR

4.2.1. Effect of applied pressure

Figure 8 shows the relationship between $P_r$ and MRR for various grain sizes with nozzle diameter 5 mm. It was found that the MRR increased more or less linearly with increase in $P_r$, all other parameters constant. This can be explained by the increase in kinetic energy imparted to the abrasive particles at higher pressures which leads to the removal of a greater volume of material.

4.2.2. Effect of standoff distance

Figure 9(a) and (b) illustrates the relationship between SoD and MRR for different abrasive particle grain size and nozzle pressure. It was found that the MRR increased with increase in SoD up to 6.0 mm, all other parameters constant, but for further increase in SoD the MRR decreased. One can conclude that, in the given circumstances, the optimum value of SoD for maximum MRR was 6.0 mm. The initial increase in MRR is mainly because at small SoDs the inter-collision of particles acts as a frictional force and causes a loss of kinetic energy, and that the small value of SoD makes it difficult for them to move away after impingement as the particles collide with the exit
Moreover, the decrease in MRR for SoD = 6.0 mm is due to a drop in kinetic energy of the particles because of the increase in distance between the exit nozzle and the impact surface (Oh & Cho, 2016).

However, Figure 9(b) makes it clear that the peak in the MRR vs. SoD curve depends very much on the applied pressure. From Figure 9(b) it can be seen that at the lowest value of $P_r (= 0.3 \text{ MPa})$, there is no peak just a gradual decrease in MRR as SoD increases. At such a low pressure, the force driving the grains of sand out of the nozzle will be relatively small and the interaction between particles will be correspondingly small, which means that the MRR will decrease as SoD increases even for small values of the SoD, due largely to the viscosity of the ambient air.

4.2.3. Effect of nozzle diameter

Figure 10 shows the relationship between nozzle diameter and MRR for different values of $d_n$. It was found that when $d_n$ increased, the MRR also increased, up to a certain limit, after which it decreased. This increase in MRR is because of the increase in flow rate of abrasive particles with larger $d_n$, a higher number of particles exit from the nozzle which results in a larger volume of material being removed. This relationship was detected for values of $d_n$ up to 5.0 mm, above this value, the MRR decreased. This is because the velocity of the particle stream is less at larger $d_n$ than for a smaller diameter which in turn leads to a reduction in the kinetic energy of the jet and decrease in MRR.

4.2.4. Effect of abrasive particle grain size

The results obtained show that increasing particle grain size generally resulted in an increase in the MRR see Figures 8-10. The increase in mass of the abrasive particles resulted in an increase in their kinetic energy and, therefore, the MRR also increased. However, it was observed that use of an
appropriate nozzle diameter was required. Figure 11 shows that for the narrowest tube, \( d_n = 4.0 \) mm, and lowest air pressure, \( P_r = 0.30 \) MPa, this effect is reversed. In these circumstances increasing particle size actually decreases MRR. This is explained as follows; when the \( d_n \) is sufficiently small with respect to \( d_g \), the flow conditions are such that inter-particle reactions introduce frictional forces that obstruct the flow. It is also known that for small orifices the thermo-viscous effects on the nozzle boundary wall layer can become important and hinder the free flow of air (Förner, Temiz, Polifke, Arteaga, & Hirschberg, 2015). Combined, these effects hinder the flow of the larger particles, especially at lower applied pressures, so the abrasive flow rate decreases and the MRR decreases.

4.2.5. Effect of impact angle

Figure 12 presents the relationship between the MRR and impact angle. It was found that the MRR increased with increasing impact angle. This is because the greater the impact angle the greater the component of the velocity perpendicular to the working surface, which causes deeper crack formation and leads to the removal of larger volumes of material (Aquaro, 2010).
5. Modelling approach

The experimental results were compared with the predictions of the erosion rate model for AJM published recently by Jafar et al. (2013) which considered the shape of craters formed by single impacts.

As previously stated, when the particles impact the workpiece with sufficient force to cause deformation, the contact area is plastically deformed resulting in lateral crack formation. Material removal takes place when the lateral crack reaches the surface (Aquaro, 2010; Bouten et al., 1999; Chen et al., 2005; Gross et al., 2013; Marshall et al., 1982; Wensink, 2002; Wensink et al., 2000). The author assumed that the lateral cracks are initiated at the bottom of the impact indentation \( a \) rather than at the bottom of the plastic zone \( b \), see Figure 13. According to Jafar’s hypothesis (Jafar et al., 2013), each particle impact is assumed to remove a spherical cap of material with a radius equal to that of the predicted lateral crack \( C_L \), and depth \( a \), see Figure 11.

The developed model estimated the mass of the material removed, \( E_p \), by a single impact as, Equation (2):

\[
E_p = \frac{\pi}{6} \rho L \left( a^2 + 3C_L^2 \right)^2 g_{\text{material/particle}}
\]  

(2)

where \( a \) and \( C_L \) can be found in terms of the mechanical engineering properties of the target material and the kinetic energy of the particle \( (U) \), respectively shown in Equations (3) and (4) (Vadgama et al., 2015).
where \( \rho_i \) is the target density in kg/m\(^3\), \( H \) is the hardness of the target in Pa, \( E \) is the elastic modulus in Pa, \( K_c \) is the fracture toughness in Pa m\(^{0.5}\) and \( U \) is the kinetic energy in N m. The kinetic energy of the particle, \( U \), is determined by:

\[
U = \frac{1}{2} m_p v_c^2
\]  

where \( m_p \) is a function of the average grain particle diameter and density and \( v_c \) is the impact velocity of the abrasive particle which is carried by air, and can be approximated by applying the Bernoulli equation as:

\[
v = \frac{d_c^2}{d_n^2} v_c
\]

\[
v_c = \sqrt{\frac{2P_t}{\rho_t}}
\]

where \( v \) is the velocity of particle stream carried by air exiting from the nozzle, \( v_c \) is the velocity of air stream in compressor hose tube, \( d_c \) is the compressor hose diameter, \( d_n \) is the nozzle diameter, and \( P_t \) is the applied pressure.

To estimate the MRR, Equation (1) has to be multiplied by the number of impacts per second, \( N_p \). The number of impacts can be calculating from the following equation:

\[
N_p = \frac{\hat{m}_a}{m_p}
\]

where \( N_p \) the number of impacts per min, \( \hat{m}_a \) is abrasive mass flow rate, which can be obtained from:

\[
\hat{m}_a = \rho_p \cdot A \cdot v = \frac{\pi d_n^2 \rho_p}{4} \text{ g/particle/min}
\]

where \( A \) is the cross sectional area of the nozzle.

MRR from the surface of the target material can be obtained from Equation (10):

\[
MRR = E_p \times N_p \text{ g/min}
\]

As a result, MRR can be predicted using the modified deterministic model, as shown in Equation (4), for different values of kinetic energy of the particles due to changes of the particle grain size, applied pressure and nozzle diameter.

Figure 14 presents MRR as a function of the kinetic energy of the abrasive particle against model predictions and experimental results. The experimental work was carried out at a constant SoD of 10.0 m, and exit tube diameter of 5.0 mm.

While the trends of the two curves are much the same, it is not so difficult to see the discrepancy between the experimental and theoretical results. An average difference of 39% was obtained over
the entire range of study. This difference may happen because the model neglects, for example, overlapping particle impacts. That motivated the authors to find another method to establish a relationship between process parameters and MRR with less error.

6. Modelling with ANN
Matlab script was coded to develop an ANN to establish a relationship between machining parameters and MRR based on experimental results which would predict the cutting performance for

![Figure 14. MRR as a function of abrasive particle kinetic energy.](image)

Notes: Dashed line indicates the trend of experimental data while the solid line shows the model predictions.

SoD = 10.0 mm.

| No. of hidden layer | Network design | Training cycles | MSE training | MSE test |
|---------------------|----------------|-----------------|--------------|----------|
| 1                   | 4 × 1 × 1      | 1,000           | 1.0165       | 0.7270   |
| 1                   | 4 × 2 × 1      | 1,000           | 0.1905       | 0.1048   |
| 1                   | 4 × 3 × 1      | 1,000           | 0.0902       | 0.0823   |
| 1                   | 4 × 4 × 1      | 1,000           | 0.0845       | 0.2914   |
| 1                   | 4 × 5 × 1      | 1,000           | 0.0244       | 0.0805   |
| 1                   | 4 × 6 × 1      | 1,000           | 0.3280       | 1.9465   |
| 1                   | 4 × 7 × 1      | 1,000           | 0.0910       | 0.6202   |
| 1                   | 4 × 8 × 1      | 1,000           | 0.7967       | 0.5926   |
| 2                   | 4 × 1 × 1 × 1  | 1,000           | 0.9869       | 0.7692   |
| 2                   | 4 × 2 × 2 × 1  | 1,000           | 0.0967       | 0.1459   |
| 2                   | 4 × 3 × 3 × 1  | 1,000           | 0.8577       | 0.9292   |
| 2                   | 4 × 4 × 4 × 1  | 1,000           | 0.3684       | 0.9357   |
| 2                   | 4 × 5 × 5 × 1  | 1,000           | 0.0009       | 0.0863   |
| 2                   | 4 × 6 × 6 × 1  | 1,000           | 0.4607       | 0.9428   |
| 2                   | 4 × 7 × 7 × 1  | 1,000           | 1.140E-5     | 0.0540   |
| 2                   | 4 × 8 × 8 × 1  | 1,000           | 0.8629       | 1.0548   |
| 3                   | 4 × 1 × 1 × 1 × 1 | 1,000         | 0.9770       | 0.7131   |
| 3                   | 4 × 2 × 2 × 2 × 1 | 1,000         | 0.9736       | 0.7659   |
| 3                   | 4 × 3 × 3 × 3 × 1 | 1,000         | 0.7848       | 0.7645   |
| 3                   | 4 × 4 × 4 × 4 × 1 | 1,000         | 0.6801       | 1.0951   |
| 3                   | 4 × 5 × 5 × 5 × 1 | 1,000         | 0.6856       | 0.7497   |
| 3                   | 4 × 6 × 6 × 6 × 1 | 1,000         | 0.7048       | 0.7957   |
| 3                   | 4 × 7 × 7 × 7 × 1 | 1,000         | 1.0503       | 0.7249   |
different values of the various inputs parameters. One, two and three hidden layers were tested for each individual performance. The inputs and output sets obtained from cutting experiments were used as training input patterns. The best network was chosen from the different network structures based on the minimum least mean squared error (MSE). Table 2 shows the MSE of the training examples using different numbers of hidden layers and varying numbers of neurons in each hidden layer.

After the MRR models were developed using input and output data sets obtained from machining experiments, they were validated using data sets not used in the training. It was found that the 4 × 7 × 7 × 1 structure network has the minimum MSE values for both the training phase and the test process. Figure 15 shows the optimum structure 4 × 7 × 7 × 1 with two hidden layers with seven neurons in which one for the four inputs parameters and the MRR as an output. Thus, this structure was considered the best structure to be used in the prediction of MRRs. Figure 16 presents the learning diagram for the network with the 4 × 7 × 7 × 1 structure, and Figure 17 shows the relationship between the measured and estimated MRRs.
7. Optimisation with GA

The ANN chosen to determine the MRR was optimised using a GA. The GA was based on the process parameters, \( P, d_n, \text{SoD}, \) and \( d_g \) to give maximum MRR. A flow chart for the GA procedure is shown in Figure 18.

Figure 19 shows generations required to find optimum fitness values. Table 3 shows the results of the optimum parameters using GA and the corresponding MRR value. The predicted optimal process parameters to give maximum MRR agreed well with what was expected based on the experimental results.
An experiment was carried out for conditions set as close as possible to optimum values to test the GA and ANN model. The experimental results showed a good agreement with the theoretical result for MRR with a difference of 8.4%, as shown in Table 4.

8. Conclusions
In this paper, a detailed study of the AJM has been undertaken that included an experimental investigation, ANN modelling and optimisation of the process parameters governing MRR.

The following are specific conclusions:

- The investigation has demonstrated that MRR increased with increase in the kinetic energy of the abrasive particles.
- It was found that applied pressure was the most significant parameter influencing MRR.
- Nozzle diameter has considerable effect on MRR. For nozzles too small or too large diameter relative to particle size, the MRR decreased.
- The MRR increased with the increase in standoff distance up to a certain limit and then the MRR decreased with the further increase of standoff distance.
- MRR increased with increase in abrasive grain size.
- Highest values of MMR occurred at an impact angle of 90°, oblique impact gave a lower MRR.
- An ANN was developed to model AJM process with small error and, once trained, could predict the MMR for any set of process parameters. It was found that $4 \times 7 \times 7 \times 1$ was the best network structure for estimating the MRR with a maximum error of 5.3%.
• The result showed that the GA is a fruitful technique to identify the optimum solutions for maximum MRR with an error of 8.4%.

• To obtain maximum MRR depends on a suitable simultaneous selection of each and every parameter; e.g. applied air pressure must be suited to the standoff distance and particles grain size must be suited to nozzle diameter.

• It is recommended to apply different optimisation techniques such as the Bees Algorithm and Fuzzy logic to evaluate their performance and determine the most appropriate method for this application.

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