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Application of crow search algorithm for the optimization of abrasive water jet cutting process parameters

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Abstract. The present work deals with the prediction of optimal parametric data-set to yield the minimum surface roughness in Abrasive Water Jet (AWJ) cutting of ceramic Tile. By means of a Box–Behnken experiment design technique, an experiment matrix with three factors and three levels was designed. Quadratic model for surface roughness was developed to fit with experimental data. Then, the improved optimal combination of the process parameters is evaluated by proposed methodology of most efficient crow search algorithm. Further, experimentally validation test has been conducted for the optimal cutting conditions suggested by crow search algorithm.

1. Introduction

Abrasive water jet cutting is a newly emerging non-traditional machining process which is used to cut tough materials[1]. In this process, high speed water jet accelerated hard abrasive particles. Then, high speed water mixed with the abrasive material impact to the workpiece, which removes the material. Because of the high velocity, the cutting could be done quickly[2]. Abrasive water jet machine cuts almost all types of materials (conductive and nonconductive). Where, the traditional machine unable to perform effectively especially on brittle and ductile materials. It is widely applied in the cutting of hard or complex-to-cut materials, such as titanium, stainless steel, aluminium alloys, etc., and it has been used in the aircraft and automobile industries[3]. Abrasive water jet machining does not use the traditional tool, so according to the material composition, structure, hardness, and the physical properties of different, abrasive water jet can be suitable process parameters selection for the processing of various materials[2]. Compared with other processing methods, the AWJ machining method has the advantages of flexible, rapid, extremely low machining force, does not have contact with tools and does not produce heat. Therefore, the considerable research and development effort has been made in recent years to develop new techniques to enhance the cutting performance of the process. Recently, many computational techniques are evolved for optimizing the machining process parameters such as Response surface Methodology, Genetic Algorithm, Particle Swarm Optimization



etc. Lima et al[4] studied the influence of the main process parameters such as traverse speed and abrasive mass flow rate on the surface finish of agates machined by AWJ cutting process. It was found that the thickness of the sample is not a predominant factor for the surface finish, when the experiments were conducted for agate plates of 5 and 10 mm thickness. It also stated that, for the economic point of view, a combination of high traverse speeds and low abrasive mass flow rates leads to reducing the process-associated costs, making AWJ an attractive machining process. Babu and Muthukrishnan[5] focused on optimising the process parameters in abrasive water jet machining with the objective of minimising surface roughness (R_a) in brass-360 material. Abrasive flow rate, pump pressure, stand-off distance and feed rate were considered as process parameters. A mathematical model developed using ANOVA in this study was found to be satisfactory which gives R^2 value of 94.91%. It has been found that the Pump pressure is the most influential factor related to surface roughness, followed by abrasive flow rate. And, the surface roughness value was improved by 33% despite an increase in Pump pressure of 25% and a decrease in abrasive flow rate of 40%. Babu and Muthukrishnan[6] further discussed on the optimization of an abrasive water jet machining process with multiple characteristics, using the Taguchi orthogonal array and grey relational analysis (GRA) in cutting of Corian aurora (tile). The performance characteristics of surface roughness and the kerf angle were optimized through the machining process variables, such as mesh size, nozzle diameter, abrasive flow rate, water pressure, stand-off distance, and feed rate. And, it is stated that the optimized parameters may be used in manufacturing industries, for improving the non-conventional machining performance in AWJ cutting. Santhanakumar et al [7] examined the effect of AWJ cutting parameters like abrasive grain size, abrasive flow rate, nozzle-workpiece standoff, water pressure and jet traverse rate on the surface roughness and taper angle of cut produced with ceramic tiles. A new combined technique of grey-based response surface methodology (g-RSM) was disclosed for obtaining the optimal level of AWJ cutting parameters. The optimal parameter setting was validated by conducting a confirmation test. The cut surfaces were also examined using field emission scanning electron microscope images, P-profile plots and atomic force microscope images. Aich et al[8] conducted on cutting of borosilicate glass by AWJ cutting process. Optimum condition of control parameters setting was searched through particle swarm optimization (PSO). Abdullah et al[9] examined the effect of cutting parameters, namely standoff distance, nozzle traverse speed, abrasive flow rate, and material type on cutting performance for two types of marble workpieces, Carrara white and Indian green. Statistical analysis was assessed to understand the influence of the cutting parameters on the process performances in terms of surface roughness, surface waviness, and Kerf taper ratio. The results showed that the traverse speed and material type were the most significant factors that affected surface roughness and Kerf taper ratio. Hajdarevic et al[3] studied the effects of material thickness, traverse speed and abrasive mass flow rate during abrasive water jet cutting of aluminum workpiece. Surface roughness was measured across of depth of cut. The experimental results show that traverse speed has great effect on the surface roughness at the bottom of the cut.

Through the literature review, abrasive water jet cutting having many capabilities regarding process efficiency and effectiveness are being investigated through theory, understanding using experimentation and process modelling techniques. but many aspects of abrasive water jet cutting technology are still under development. Therefore, the present study to explore the optimum combinations of the abrasive water jet cutting process parameters in cutting of ceramic tile using a new type of crow search algorithm. The experiments were designed on the basis of the response surface methodology (RSM) based box-behnken design (BBD) technique. Through RSM[10], a mathematical model for surface roughness is developed. Further, a proposed crow search algorithm is used to obtain the optimum parametric setting for abrasive water jet cutting process parameters for yielding the minimum surface roughness.

2. Experimental work



Figure 1. CNC controlled AWJ Machining Centre

The CNC controlled OMAX 2652 AWJ machining centre, which is imported from the Germany, is used for carrying out the experimental work. The CNC controller based abrasive water jet cutting machine includes the following basic components: high pressure pump, abrasive water jet cutting head, abrasive delivery system, abrasive material and water catcher, and x-y positioning table. There is a large number of process parameters associated with the AWJM process but it is practically impossible to include all these parameters during experimentation. The experiments were planned using response surface methodology based box-behnken design method to obtain the independent, interactive, and higher order effects of different process variables on surface roughness.

Table 1. Process Parameters and Levels`

Process parameters	Reference symbol	Units	Low(-1)	Centre(0)	High(+1)
Water jet pressure	X_1	bar	2000	3000	4000
Jet traverse speed	X_2	mm/min	150	200	250
Abrasive flow rate	X_3	g/min	300	400	500
Standoff distance	X_4	mm	1	2	3

Experimental range of process parameters and the levels of the independent variables are presented in Table 1, where -1 corresponds to the lower(minimum) value and +1 to the higher (maximum) value of each process variable. Four input process parameters namely the water jet pressure, jet traverse

speed, abrasive feed rate and standoff distance, were considered. The values of X_1 (Water Jet Pressure) varied between 2000bar and 4000bar, X_2 (Jet traverse speed) between 150 mm/min and 250mm/min, X_3 (Abrasive flow rate) between 300 g/min and 500 g/min, and X_4 (Standoff Distance) between 1mm and 3mm. This BBD design scheme required 29 experimental runs. The other parameters that were kept constant during the tests included the nominal jet impact angle (90°), orifice diameter (0.3 mm), mixing tube or nozzle diameter (1.2 mm) and abrasive material (80 mesh garnet). A typical ceramic tile with dimension of the material is $300 \times 50 \times 10$ mm thick plate is used for experimental work as shown in Figure 2. Because, ceramics are a large group of structural materials characterized by many useful properties. The most important are the high heat resistance, resistance to chemical agents, good mechanical properties and good dielectric and insulation properties[11]. The specimen was cut into $50 \text{ mm} \times 10 \text{ mm}$ slot through depth of 10 mm. The cutting zone of AWJ process as illustrated in Figure 3. All the experiments were conducted randomly to minimize the effects of unexplained variability in the observed responses because of externally influencing factors.



Figure 2. Ceramic Tile Specimen

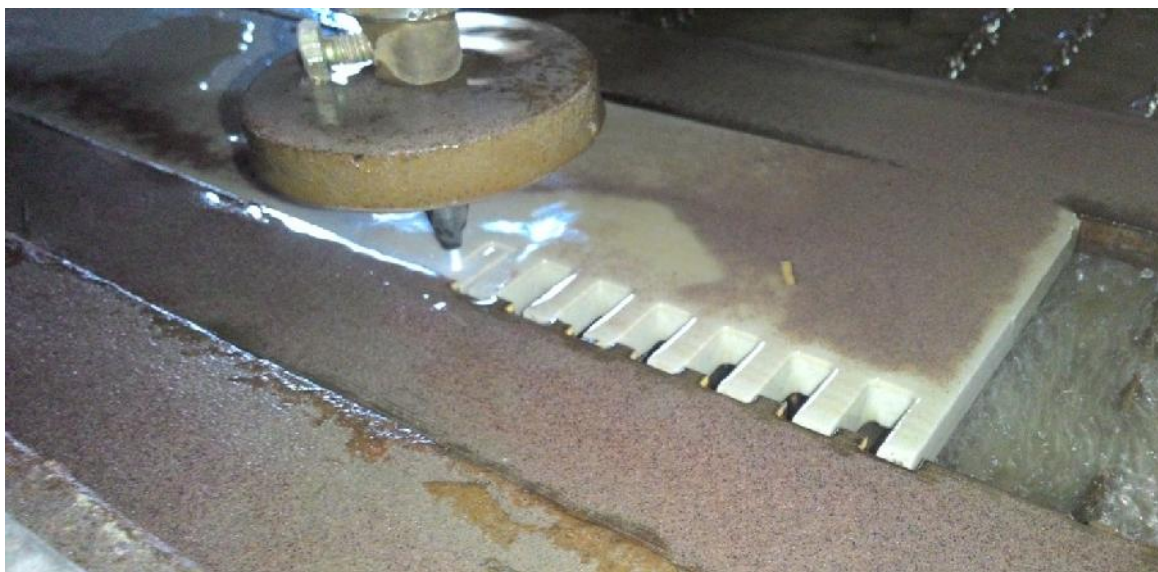


Figure 3. AWJ cutting zone

Average arithmetic surface roughness, measured at 10 different locations on striation free zone of cut surface (R_a) – to be measured in microns using Maher Perth meter M1. The measurements were repeated twice and their average values used. In parts manufacturing, accuracy of the shape and dimension, and surface finish are the primary quality objectives. Surface roughness is the irregularity in the cut materials surface texture. Roughness becomes important when abrasive water jet machining produces parts requiring high quality. Therefore, in this study, the arithmetic average of the roughness was measured and used for further analysis.

Table 2. Experimental plan and collected responses

Exp.No	Process parameter				Response	
	Water Pressure	Jet	Jet traverse speed	Abrasive flow rate	Standoff Distance	Surface roughness
	bar		mm/min	g/min	mm	Micron
1	2000		150	400	2	2.173
2	4000		150	400	2	1.471
3	2000		250	400	2	2.407
4	4000		250	400	2	1.906
5	3000		200	300	1	2.641
6	3000		200	500	1	2.541
7	3000		200	300	3	3.277
8	3000		200	500	3	3.009
9	2000		200	400	1	1.906
10	4000		200	400	1	1.571
11	2000		200	400	3	2.792
12	4000		200	400	3	2.001
13	3000		150	300	2	2.641
14	3000		250	300	2	3.126
15	3000		150	500	2	2.675
16	3000		250	500	2	2.742
17	2000		200	300	2	2.474
18	4000		200	300	2	1.906
19	2000		200	500	2	2.34
20	4000		200	500	2	1.672
21	3000		150	400	1	2.34
22	3000		250	400	1	2.441
23	3000		150	400	3	2.842
24	3000		250	400	3	3.210
25	3000		200	400	2	3.109
26	3000		200	400	2	3.206
27	3000		200	400	2	3.226
28	3000		200	400	2	3.205
29	3000		200	400	2	3.207

3. Model development and ANOVA analysis

A box-behnken design is constructed using the software Design Expert (8.0.6 version) and was used to analyze the results of collected surface roughness as indicated in Table 2. The final quadratic model for surface roughness is represented as follows (uncoded units)

$$\text{Surfaceroughness} = -13.66927 + 0.0053634X_1 + 0.048620X_2 + 0.014139X_3 + 1.16228 X_4 + 0.000001005X_1X_2 - 0.000114X_1X_4 - 0.0000209 X_2X_3 + 0.001335 X_2X_4 - 0.00000938925X_1^2 - 0.00010782 X_2^2 - 0.00001358X_3^2 - 0.19493 X_4^2 \quad (1)$$

Table 3. ANOVA Table for surface roughness

Source	Sum of Squares	df	Mean Square	F value	Prob > F
Model	8.461774	14	0.604412462	332.5497	< 0.0001
X_1	1.059099	1	1.059099188	582.7198	< 0.0001
X_2	0.238008	1	0.238008333	130.9529	< 0.0001
X_3	0.098282	1	0.098282118	54.07513	< 0.0001
X_4	1.13529	1	1.135290083	624.6402	< 0.0001
X_1X_2	0.0101	1	0.01010025	5.55719	0.0335
X_1X_4	0.051984	1	0.051984	28.60176	0.0001
X_2X_3	0.043681	1	0.043681	24.03343	0.0002
X_2X_4	0.017822	1	0.01782225	9.805859	0.0074
X_1^2	5.718353	1	5.71835282	3146.256	< 0.0001
X_2^2	0.471291	1	0.471290672	259.3056	< 0.0001
X_3^2	0.119621	1	0.119620733	65.81571	< 0.0001
X_4^2	0.246459	1	0.246459469	135.6028	< 0.0001
Residual	0.025445	14	0.00181751		
Lack of Fit	0.01682	10	0.001681995	0.780037	0.6599
Pure Error	0.008625	4	0.0021563		
Cor Total	8.48722	28			
Std. Dev.	0.042632		R^2	0.997	
Mean	2.55369		Adj R^2	0.994	
C.V. %	1.669438		Pred R^2	0.986	
PRESS	0.11036		Adeq Precision	58.902	

Analysis of variance (ANOVA) [12] was conducted to fit the mathematical model (equation (1)) to examine the statistical significance of the model terms. The adequacy of the models was determined using model analysis, lack-of-fit tests, coefficient of determination (R^2), Adj R^2 , Pred R^2 and Adequate Precision. The calculated values of the determination coefficient (R^2) and adjusted determination coefficient (Adj. R^2) are more than 95%, which indicates a high significance of the model. Pred. R^2 is the correlation coefficient in prediction, which is more desirable when approaching unity. Therefore, the fitted quadratic model is reliable, and can be employed in optimization of the test

output. The ANOVA of the quadratic regression model indicated that the model was highly significant, as the F value for the model was 332.5497. There was only a 0.01% chance that the “model F value” this large could occur because of noise. The p value $\text{Prob}>F$ value of the model was <0.0001 , which also confirmed that the model was highly significant. Lack-of-fit test was also carried out, which measures the failure of a model to represent the data in the experimental domain at points which are not included in the regression. A lack of-fit value of 0.780037 implies that the lack of fit is not significant relative to the pure error when p ($0.6599 > 0.05$) also supports the fitness of the model. A normal probability plot of the residuals is depicted in Figure 5, which reveals that the residuals generally fall on a least-square line which is used to estimate the cumulative distribution function for the population. As evident from the figure, the errors are normally distributed and there are almost no serious violations of the assumptions that underlie the analysis[13].

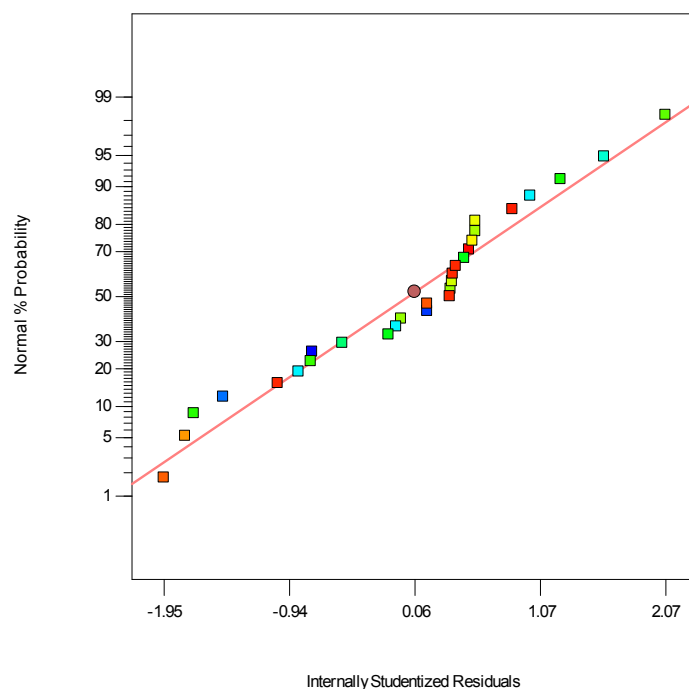


Figure 4. Normal probability plot

4. Optimization by crow search algorithm

The step by step procedure for the implementation of crow search algorithm[14] as follows:

Step 1: Initialize problem and adjustable parameters

The optimization problem, decision variables and constraints are defined. Then, the adjustable parameters of CSA (flock size(N), maximum number of iterations(iter_{\max}), flight length(l) and awareness probability(AP)) are valued.

Step 2: Initialize position and memory of crows

N crows are randomly positioned in a d -dimensional search space as the members of the flock. Each crow denotes a feasible solution of the problem and d is the number of decision variables.

$$crows = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_d^1 \\ x_1^2 & x_2^2 & \cdots & x_d^2 \\ \vdots & \vdots & \vdots & \vdots \\ x_1^N & x_2^N & \cdots & x_d^N \end{bmatrix} \quad (2)$$

The memory of each crow is initialized. Since at the initial iteration, the crows have no experiences, it is assumed that they have hidden their foods at their initial positions.

$$Memory = \begin{bmatrix} m_1^1 & m_2^1 & \cdots & m_d^1 \\ m_1^2 & m_2^2 & \cdots & m_d^2 \\ \vdots & \vdots & \vdots & \vdots \\ m_1^N & m_2^N & \cdots & m_d^N \end{bmatrix} \quad (3)$$

Step 3: Evaluate fitness(objective) function

For each crow, the quality of its position is computed by inserting the decision variable values into the objective function.

Step 4: Generate new position

Crows generate new position in the search space as follows: suppose crow i wants to generate a new position. For this aim, this crow randomly selects one of the flock crows (for example crow j) and follows it to discover the position of the foods hidden by this crow(m^j). The new position of crow i is obtained by the equation as below:

$$x^{i,iter+1} = \begin{cases} x^{i,iter} + r_i \times (m^{j,iter} - x^{i,iter}) & r_j \geq AP^{j,iter} \\ randomposition & otherwise \end{cases} \quad (4)$$

This process is repeated for all the crows.

Step 5: Check the feasibility of new positions

The feasibility of the new position of each crow is checked. If the new position of a crow is feasible, the crow updates its position. Otherwise, the crow stays in the current position and does not move to the generated new position.

Step 6: Evaluate fitness function of new positions

The fitness function value for the new position of each crow is computed.

Step 7: Update memory

The crows update their memory as follows:

$$m^{i,iter+1} = \begin{cases} x^{i,iter+1} & f(x^{i,iter+1}) \text{ is better than } f(m^{i,iter}) \\ m^{i,iter} & otherwise \end{cases} \quad (5)$$

Where $f(.)$ denotes the objective function value.

It is seen that if the fitness function value of the new position of a crow is better than the fitness function value of the memorized position, the crow updates its memory by the new position.

Step 8: Check termination criterion

Steps 4-7 are repeated until $iter_{max}$ is reached. When the termination criterion is met, the best position of the memory in terms of the objective function value is reported as the solution of the optimization problem.

According to the above crow search algorithm, at first, mathematical models of polynomial type are developed to correlate the AWJ machining parameters and performance measures. Once the process model of surface roughness is constructed, an appropriate objective function and constraints are developed with the process models. The optimization process of crow search algorithm is implemented Matlab software in order to find the optimal solution of surface roughness. The crow search is expected to give the minimum value of surface roughness for abrasive water jet cutting process. The convergence plot of surface roughness value over max number of generations using crow search algorithm is shown in Figure 5, which illustrates the algorithm, converges up to 200 generations.

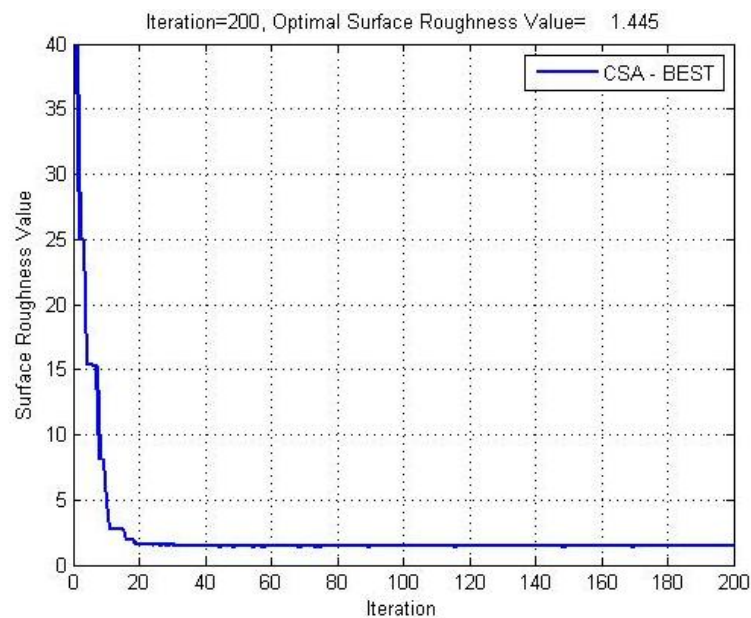


Figure 5. Convergence plot

Table 4. Comparison between the initial experimental condition and optimal condition achieved by CS algorithm

Model Summary		Initial condition	Optimal condition	% of improvement
Process parameters	Water Jet Pressure(bar)	2000	3997.19	
	Jet traverse speed(mm/min)	150	152.05	
	Abrasive flow rate(g/min)	400	381.08	
Corresponding response parameters	Standoff distance(mm)	2	1.62	
		2.173	1.445	33.5

Table 5. Experimental validation of optimal parameter settings

	Water Jet Pressure(bar)	Jet traverse speed(mm/min)	Abrasive flow rate(g/min)	Standoff Distance(mm)	Surface roughness(Micron)
Predicted by CS algorithm	3997.19	152.05	381.08	1.62	1.445
Experimental	3997.19	152.05	381.08	1.62	1.456
% Error					0.7612

On the other hand, the percentage of improvement of fitness value to corresponding optimal condition is achieved by 33.5%(Table 4) , and it is clear that the predictive capability of the crow search algorithm. After the selection of AWJ optimal process parameters, further experiments were carried out to verify the corresponding surface roughness predicted by algorithm. Table.5 shows that the percentage of error between the predicted and experimented values. From this analysis, it is observed that the calculated error(i.e. 0.7612) is very small which confirms the excellent reproducibility of the experimental conditions.

5. Conclusions

In this paper, a response surface methodology and PSO algorithm has been introduced for abrasive water jet cutting of ceramic tile. The present approach comprises two stages. Mathematical model is developed to predict the surface roughness in stage 1. Stage 2 involves the optimization of process parameters using the crow search algorithm. From the proposed approach, the following conclusions are drawn.

1. The Box-Behnken design approach is used for experimental design. The water jet pressure, Jet traverse speed, abrasive flow rate and standoff distance were chosen as process parameters or factors , and three levels of each factor were considered in the experimental design. As response variable of surface roughness was taken into consideration.
2. The predicted values match the experimental values reasonably well, with R^2 of 0.997 for surface roughness. Thus the developed model is more suitable for further analysis.
3. The social behaviour of crows is an effective model for constructing the crow search algorithm.
4. The optimal performance characteristics are observed to have minimum surface roughness when the process parameters are water jet pressure(3997.19bar), Jet traverse speed (152.05mm/min), abrasive flow rate (381.08 g/min) and standoff distance (1.62mm).
5. A significant improvement in surface roughness characteristics is observed at the optimum parameter settings in comparison to the initial settings.

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