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ORIGINAL ARTICLE

Multi response optimization of process parameters based on Taguchi—Fuzzy model for coal cutting by water jet technology

Vinay Sharma · Somnath Chattopadhyaya · Sergej Hloch

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Abstract The process of material cutting and fracture by high velocity water jets is a complex series of phenomena which may involve compression, tension, shear, erosion, wears, cracking, wave propagation, and cavitations damage. This makes the exact analysis of the jet cutting process to be very complicated. The problem of water jet coal cutting is a multiresponse problem. There are two output variables, depth of cut and cutting width whose optimization will result in the increase in the productivity of coal cutting. In this paper, a Taguchi–Fuzzy decision method has been used to determine the effective process parameters for improving the productivity of coal mines. The Taguchi method of experimental design is a widely accepted technique used for producing high quality products at low cost. The optimization of multiple responses in complex processes is common; therefore, to reduce the degree of uncertainty during the decision making, fuzzy rule-based reasoning was integrated with the Taguchi loss function.

Keywords Water jet · Coal cutting · Taguchi techniques · Fuzzy logic · Productivity

1 Introduction

The continuous jet is the most common type of working water jet, and is used for most industrial and commercial cleaning and cutting applications [1–3]. These jets are used over an extremely wide range of system pressure and rates of water flow through the nozzles [2, 4].

In water jet cutting of coal, high-pressure water is focused through a nozzle to create a high-velocity water stream [4–8]. When the water jet is moved across the coal surface [9, 10], it penetrates into existing cracks, weakness planes and grain and crystal boundaries, there by dislodges the material [4, 11]. So in order to understand the mechanisms of water jet cutting system and to develop a high productivity system, it is necessary to first analyze the cutting mechanism of the water jet and then obtain an optimum combination of the effective process parameters [3, 12].

For investigating the effect of the different process parameters of water jet on cutting coal, the mining condition was imitated in the laboratory. From the survey conducted with the help of the engineers from the Central Coal Field limited, India, and the feasibility study carried out based on the survey results, it was found that coal mines of Upper Sirka Seam of SAUNDA-D Coal Mines, Barkakana Jharkhand, India have the maximum of the desired properties that required for successful implementation of water jet technology.

The samples were collected by manually removing the coal blocks from the mines to minimize the micro-cracks generated by blasting. These samples were obtained from different locations of the mines to take care of all

V. Sharma
Department of Production Engineering,
Birla Institute of Technology,
Mesra,
Ranchi 835215, India
e-mail: somuismu@gmail.com

S. Chattopadhyaya
Department of ME & MME, Indian School of Mines,
Dhanbad 835215, India
e-mail: somuismu@gmail.com

S. Hloch (✉)
Department of Manufacturing Management,
Faculty of Manufacturing Technologies,
Technical University of Košice with a seat in Prešov,
080 01 Prešov, Slovakia
e-mail: sergej.hloch@tuke.sk

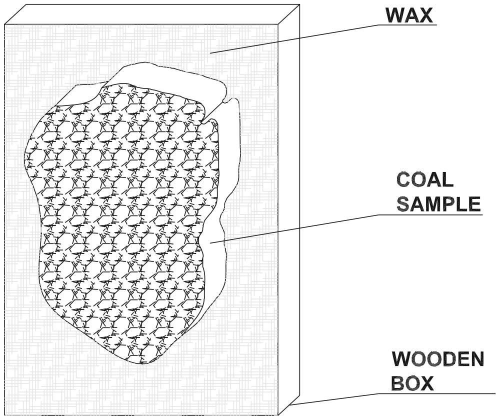

Fig. 1 Schematic view of the coal sample kept inside the wax pool

the possible variation of sample proprieties present in that mine. The variation in the coal properties occurs due to the presence of different impurities in the mines. After removing, the coal samples were sealed in the plastics bag inside the mine itself to reduce any change in its properties due to environmental effects during transportation.

To simulate the actual mining conditions and obtain good results, it was decided to apply compressive forces all around the coal sample in the laboratory leaving only the face as was found in the mine. To do this, wax was poured into a frame set around the coal so as to give at least 5–10 cm thick coating of wax on all the five sides of the specimen as shown in Fig. 1. This technique has helped to impart the compressive forces as found in the actual conditions. Apart from this, the sealing of coal with wax also helped to reduce any change in the properties of samples during experimental investigations because the samples were brought at a time and they were tested over a long span of time. Also, the wax coating insured that there would not be any degradation of the coal during the subsequent preparation procedures. The wax also provides necessary confinement to the coal sample otherwise the sample expand laterally under the impact and split it apart. Once the samples were sealed in the wax, the blocks were moved to the laboratory. The free face was cut perpendicular to the bedding plane. Care was taken to insure that each sample was thick enough to avoid the possibility of the jet cutting through the coal into the wax. To reduce any internal stress generated or cracks developed during the preparation of the face, the cutting of face was done by hand using a cross-cut saw. After preparing the coal sample as mentioned, it was mounted on the target table with the help of the fixture developed in such a way that it will maintain proper seam angle as it is maintaining in the mines and the experiments were carried out based on the method proposed by the Taguchi.

2 Experimental investigation based on Taguchi technique

As both the machine and material were new, so it was decided to conduct a lot of initial experiments to analyze the effect of individual parameters on depth of cut and kerf width [4, 5]. These experiments have helped in determining the limitations of system and material, and they are as follows:

2.1 Machine limitations

1. The first limitation with regard to machine parameters was the nozzle diameter. It was found that if the nozzle diameter was increased above 1 mm, then the desired pressure required for the coal cutting was not developed by the existing machine.
2. The second limitation with regard to machine was the traversed rate. As a large variation of the range was not present
3. The water was supplied to the head through a mechanical foot valve due to which losses were there.

2.2 Material limitations

As it was already mentioned that the samples of the coal were taken from the mine situated 100 km away from the laboratory. So after taking the samples from mine, a lot of precautions were taken to preserve them from any contaminations/degradations by atmosphere till they were cut by water jet. But still, it was found that each sample was

Fig. 2 Factor–characteristic relation diagram for coal cutting

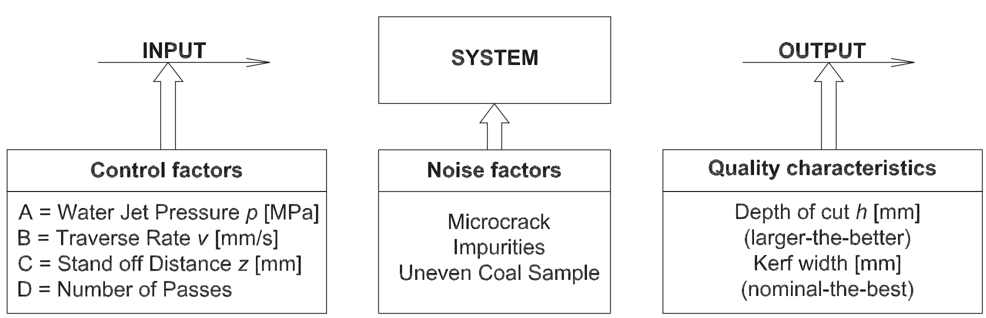

Table 1 Factors and levels tested in the experiments

Factor	Factor description	Test level 1	Test level 2	Test level 3
A	Water jet pressure (Kgf/Cm^2)	150	300	450
B	Jet traverse rate (mm/s)	13.07	18.41	24.75
C	Standoff distance (mm)	05	10	15
D	Number of pass	01	02	03

behaving differently when subjected to cutting. After a due analysis, it was found that this was mainly due to the following main reasons:

1. The samples were of different size
2. The shape of the samples were not uniform due to variations in all directions
3. A lot of micro-cracks were there inside the samples which were generated during the removal process of the sample from the mine as well as during preparation process of the samples.
4. The properties of the samples were different due to the presence of the impurities
5. To maintain the standoff distance, the top of the samples were cut by mechanical hacksaw, it was found that still the top surface was not smooth and which varies the standoff distance along the cut length.
6. Though precautions were taken to prevent the samples from atmospheric contaminations but the method was not full proof and effects were found with respect to time

After finding the limitations of the system, i.e., noise it was decided to analyze the effect of the controllable parameters, i.e., signal on the system to achieve the desired output.

There are four parameters which affect the process. They are pressure (A), traverse rate (B), standoff distance (C), and number of passes (D). We have not considered the nozzle diameter as the controlling parameters because it was found from the initial experiments that with the increase in nozzle diameter the desired pressure for cutting the coal, were not achieved (machine limitation).

The desired output is maximum productivity, i.e., the volume of the coal cut/removed from the mine or in other words it can be said that the desired output is large depth of cut and optimum kerf width. This is because the maximum depth of cut will enhance the volume of material removed and optimum kerf width will make it possible for the operator to enter the nozzle inside the cut portion to maintain the stand of distance and hence maintain the cutting rate. Therefore, the first output response (depth of cut) belongs to larger-the-best category and the second response (kerf width) belongs to nominal-the-best category.

The factors controlling the cutting efficiency and the noise factors present in the experiment were summarized in Fig. 2.

As there were four variables present in the system and interaction was not present, so it was decided to use the L9 orthogonal array, i.e., tests were performed using a three level nine run experimental design. Four independent variables associated with the water jet cutting process viz. pressure, traverse rate, standoff distance, and number of passes was varied. As recommended by Taguchi, a randomized sequence of experiment was conducted using random tables in order to eliminate the influence of systematic errors. Three observations were taken at three different samples for each experimental design point or condition in order to reduce the noise or the limitations of the material and machine. Again for each experiment, the data were collected from three different points on the cut zone and the average of which was taken as the output data of that experiment. This was done in order to minimize

Table 2 Orthogonal array l9 and resulting experimental data for kerf depth and kerf width

X. no	Random order	Factors				Experimental data							
		A	B	C	D	AK_{d1}	AK_{d2}	AK_{d3}	S/N Ratio (DB)	AK_{w1}	AK_{w2}	AK_{w3}	S/N Ratio (DB)
1.	5	1	1	1	1	11	10	07	19	4	8	7	10
2.	7	1	2	2	2	21	14	20	25	15	25	19	12
3.	8	1	3	3	3	24	24	26	28	27	22	27	19
4.	4	2	1	2	3	61	71	64	36	20	22	13	12
5.	2	2	2	3	1	68	74	69	37	30	34	27	19
6.	1	2	3	1	2	47	42	45	33	19	16	12	13
7.	3	3	1	3	2	82	70	73	37	39	43	37	22
8.	6	3	2	1	3	87	95	89	39	19	15	23	14
9.	9	3	3	2	1	39	37	43	32	27	18	14	09

Table 3 ANOVA for depth of cut

Source	Sum of square	Degree of freedom	Mean square	F	Contribution (%)
A	267	2	133.5	11.87	56.7
B	18	2	9	–	03.8
C	27	2	13.5	1.20	05.7
D	159	2	79.5	7.07	33.8
Error	0	0	–	–	
Total	471	8	–	–	100
(Error)	45	(4)	11.25		

Table 4 ANOVA for kerf width

Source	Sum of square	Degree of freedom	Mean square	F	Contribution (%)
A	4.67	2	2.34	1	2.76
B	4.67	2	2.34	1	2.76
C	143.37	2	71.69	30.64	84.64
D	16.67	2	8.34	3.56	9.84
Total	169.38	8			100
(Error)	9.34	(4)	2.34		

internal variations within the sample. Each reading recorded was then rounded to its nearest decimal value. Table 1 contains the levels of each variable used for the experiments and Table 2 contains the observed values.

A better feel for the relative effects of the different factors can be obtained by the decomposition of variance, which is commonly called analysis of variance (ANOVA). ANOVA is also needed for estimating the error variance for the factor effects and the variance of the prediction error. In the interest of gaining the most information from a matrix experiment, all or most of the columns should be used to study process or product parameters. As a result, no degrees of freedom may be left to estimate error variance. Indeed, this is the situation for the present case also. In such case, the direct estimation of the error variance cannot be made. However, an approximate estimate of the error variance can be obtained by pooling the sum of squares corresponding to the factors having the lowest mean square. As a rule of thumb, it was suggested [13–16] that the sum of squares corresponding to the bottom half of the factors (as defined by lower mean square) corresponding to about half of the degrees of freedom be used to estimate the error mean square or error variance. This rule is similar to considering the bottom half harmonics in a Fourier expansion as error and using the rest to explain the function being investigated. Error variance computed in this manner is indicated by parentheses and the computation method is called pooling.

Based on the above theory, the calculation for the affect of different process parameters on the depth of cut and kerf width was estimated. As already mentioned for the first output response, depth of cut, the problem was considered to be larger-the-better type. The ANOVA analysis for the same has been summarized in Table 3 and effects of different factors are shown graphically in Fig. 3.

Similarly, the analysis was carried out for the kerf width and results were tabulated in Table 4 and the separate effect of each factor on kerf depth is shown graphically in Fig. 4. For this second output response (i.e., Kerf width), the condition was assumed as the nominal-is-best.

3 Interpretation from ANOVA tables

From the ANOVA shown in Table 3, it can be noticed that factor A (i.e., pressure) makes the larger contributions nearly 56.7%. Factor D (number of passes) makes the next largest contribution, i.e., 33.8%. Factors B and C together

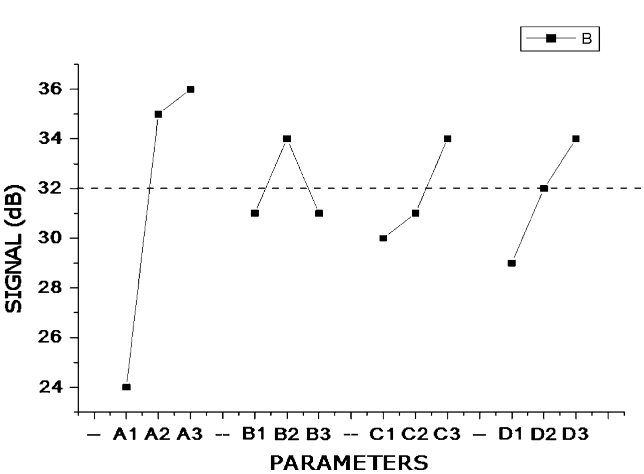

Fig. 3 Factors effects on depth of cut

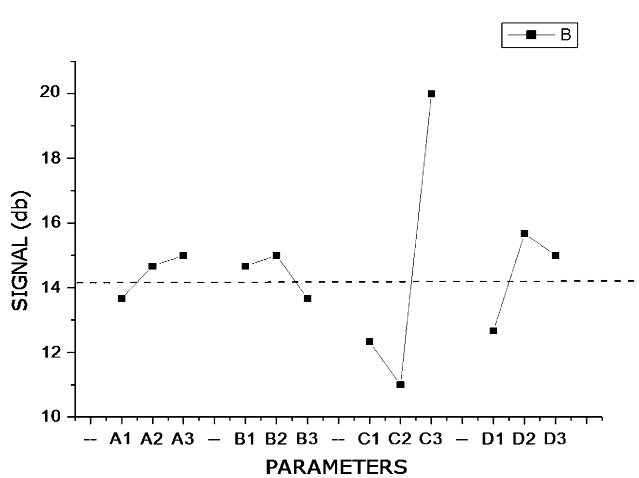

Fig. 4 Factors effects on kerf width

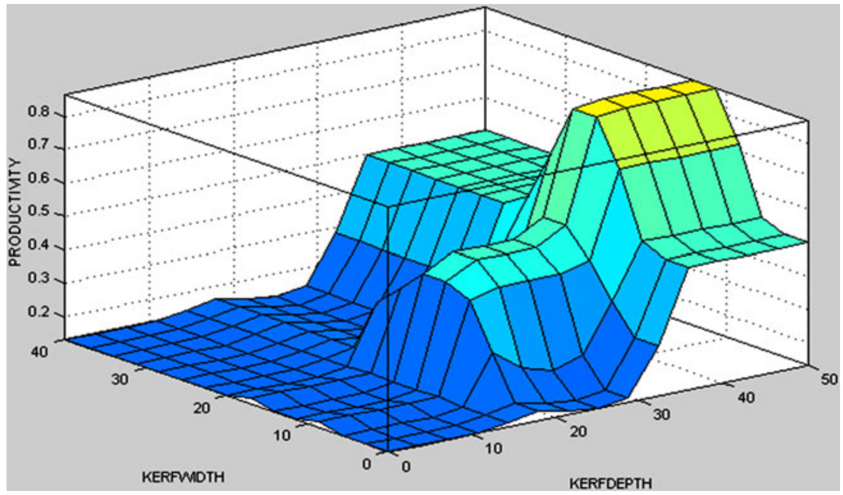

Fig. 5 Effect of kerf width and kerf depth on productivity

make only 9.5% contributions to the depth of cut. The larger the contribution of a particular factor to the total sum of squares, the larger the ability is of that factor to influence "η".

Similarly, it can be seen from the ANOVA shown in Table 4 that the parameter which makes a large effect on the kerf width is the standoff distance (parameter C) and apart from this other parameters have very less effect. There is a very little contribution of parameter "number of passes" (parameter D) on kerf width.

From these two ANOVA tests, it can be found that out of the four parameters, only three parameters (i.e., pressure, standoff distance, and number of passes) have large contribution and the fourth parameter, i.e., traverse rate has very less effect.

The main aim of the present analysis is to determine the combination of parameters which have large effect on the productivity.

As it has already been mentioned that to have large productivity, the kerf depth should be maximum and kerf width should be optimum. But from the above analysis, it was found that the parameters which have large effect on the depth of cut are different from that of kerf width. So in order to optimize both the parameters simultaneously and to have maximum productivity, the concept of fuzzy logic was used.

Table 5 Orthogonal array for productivity

Ex. no.	Factors				Productivity
	A	B	C	D	
1.	1	1	1	1	0.491
2.	1	2	2	2	0.5
3.	1	3	3	3	0.294
4.	2	1	2	3	0.858
5.	2	2	3	1	0.576
6.	2	3	1	2	0.608
7.	3	1	3	2	0.5
8.	3	2	1	3	0.869
9.	3	3	2	1	0.5
Total					5.196
Average					0.5773

4 Optimization of multi-responses using Fuzzy rule-based inference system

For multiple response problems [17–19], it is important that we need to optimize them simultaneously rather than optimizing one response at a time. In the above case, if the final solution is left to engineering judgment and experience then it will be more subjective in nature; because of the above problems, it was decided to analyze the case using signal–noise ratio (SNR) and fuzzy rule-based inference. Fuzzy rules are derived from the knowledge and experience. Through inference, the two SNR values will be mapped into a single performance index called Multiple Performance Statistic output, upon which the optimum level settings can be identified. Instead of leaving it to engineering guesswork, this is a much more

Table 6 ANOVA for productivity

Source	Sum of square	Degree of freedom	Mean square	F	Contribution (%)
A	0.3138	2	0.1569	7.4360	65.46
B	0.056	2	0.028	1.327	11.68
C	0.0675	2	0.0338	1.5995	14.08
D	0.0421	2	0.0211	–	08.78
Error	0	0	–	–	
Total	0.4794	8			
(Error)	0.0421	2	0.0211		

structured and rigorous methodology that delivers more convincing results.

For doing the analysis, MAT LAB 6.1 was used. For analysis, Mamdani inference engine was used and centroid method was utilized for defuzzification. The S/N ratio as obtained from the experiment and tabulated in Table 2 was divided into three fuzzy set they are:

Low, <20;
Medium, 15–35;
High, >30.

For low, the membership function was taken as zmf and for high the member ship function was taken as smf where as for medium range the trimf membership function was taken. Similarly for the second input, i.e., kerf width parameters are follows:

Condition	Range	Membership function
Low	<10	zmf
Medium	5–21	trapmf
High	>15	smf

and for output parameters "Productivity" the conditions are were as follows:

Condition	Range	Membership function
Low	<0.4	zmf
Medium	0.2–0.8	trimf
High	>0.6	smf

For the analysis, nine rules were formulated as follows and results has been shown graphically in Fig. 5.

Serial no	Kerf depth	Kerf width	Productivity
1.	Low	Low	Low
2.	Low	Medium	Low
3.	Low	High	Low
4.	Medium	Low	Low
5.	Medium	Medium	Medium
6.	Medium	High	Low
7.	High	Low	Medium
8.	High	Medium	High
9.	High	High	Medium

Based on the above rules, the S/N ratio for kerf depth and kerf width (Table 3) where put into the fuzzy inference and the respective data for the productivity was obtained. The same has been tabulated in Table 5. Based on this data for productivity, the ANOVA analysis was done (Table 6).

5 Conclusion

It was found that the parameters which affect the productivity in descending order are as follows: pressure (65.46%), standoff distance (14.08%), traverse rate (11.68%), and number off passes (08.78%). It was interesting to find that the parameter traverse rate was found to have no effect when the output responses were analyzed individually. But when they were analyzed simultaneously, it was found that traverse rate have an effect of 11.68%. Similarly, the parameter number off passes which has been found to be one of the important parameter initially, found to have least effect on productivity in multi response analysis.

The best combination of parameter as found from final analysis (Table 6) was found to be pressure at range 300 Kgf/cm^2, traverse rate at 18.41 mm/s, standoff distance at 5 mm and number of passes to be 3.

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