MULTI RESPONSE OPTIMIZATION OF PROCESS PARAMETERS BASED ON TAGUCHI- FUZZY MODEL FOR COAL CUTTING BY WATER JET TECHNOLOGY

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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 multi response problem. There are two output variables, depth of cut and cutting width whose optimization will results 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

I. INTRODUCTION

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

In water jet cutting of coal, high-pressure water is focused through a nozzle to create a high-velocity water stream. When the water jet is moved across the coal surface, it penetrates into existing cracks, weakness planes and grain and crystal boundaries, there by dislodges the material. 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.

For investigating the effect of the different process parameters of water jet on cutting coal the mining condition were 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 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 to 10cm 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.

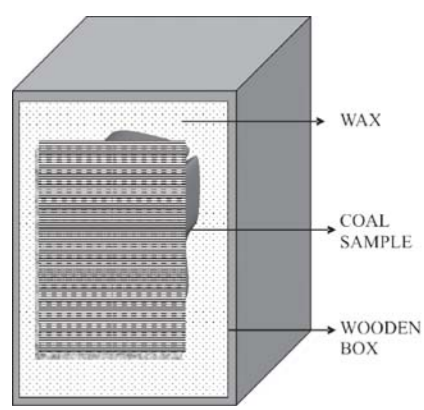

Fig. 1. Schematic view of the coal sample kept inside the wax Pool

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.

II. 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 the out come of the same has already been published[12, 13].

Based on the outcome of initial investigations it was found that there are four parameters which affects the process. They are *pressure (A), traverse rate (B), stand off distance(C), and number of passes (D).*

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 out put response (Depth of Cut) belongs to larger-the best category and the second response (Kerf Width) belong to nominal the best category.

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

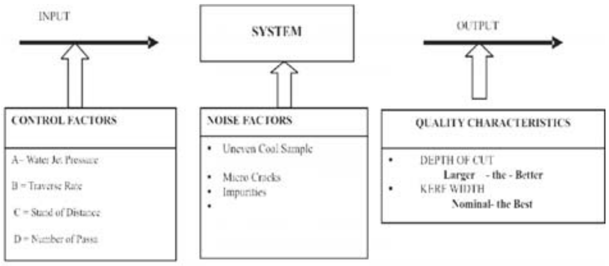

Fig. 2. Factor- characteristic relation diagram for coal cutting

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. 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 out put data of that experiment. This was done in order to minimize internal variations within the sample. Each reading recorded was then rounded of to its nearest decimal value. Table 1 contains the levels of each variable used for the experiments and table 2 contains the observed values.

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/sec)	13.07	18.41	24.75
C	Stand Off Distance (mm)	05	10	15
D	Number Of Pass	01	02	03

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**

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 can not 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 [5, 6, 7] 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 out put 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 figure 3.

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**		

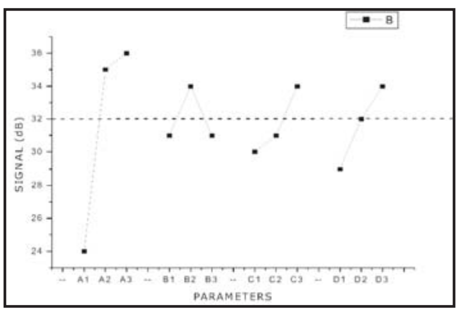

Fig. 3. Factors effects on depth of cut

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.

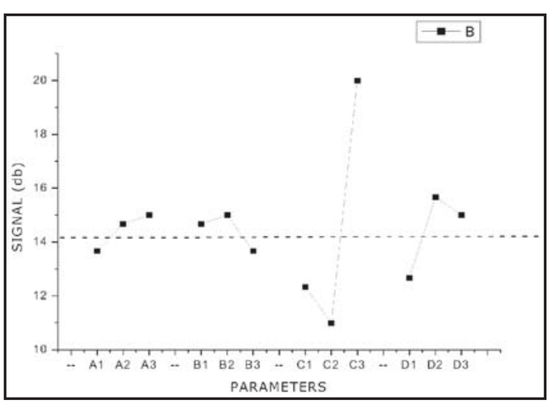

Fig. 4. Factors effects on kerf width

III. INTERPRETATION FROM ANOVA TABLES

From the ANOVA 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 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 "".

Similarly it can be seen from the ANOVA table 4 that the parameter which makes a large effect on the kerf width is the stand off 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.

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**		

From these two ANOVA tests it can be found that out of the four parameters only three parameters (i.e. pressure, stand off 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.

IV. OPTIMIZATION OF MULTI RESPONSES USING FUZZY RULE BASED INFERENCE SYSTEM [11]

For multiple response problems, 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 SNR (Signal-Noise- Ratio) 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 (MPS) output, upon which the optimum level settings can be identified.

Instead of leaving it to engineering guesswork, this is a much more 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 less than 20

Medium 15-35

High greater than 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	less than 10	(zmf)
Medium	5- 21	(trapmf)
High	greater than 15	(smf)

And for out put parameters "Productivity" the conditions are as follows

CONDITION	RANGE	MEMBERSHIP FUNCTION
Low	Less than 0.4	(zmf)
Medium	0.2 – 0.8	(trimf)
High	Greater than 0.6	(smf)

For the analysis following nine rules were formulated as follows and same 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

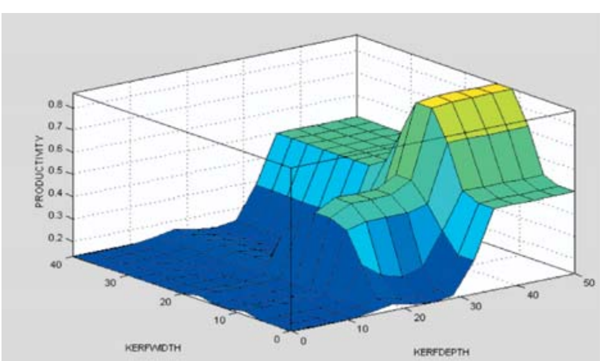

Fig. 5. Effect of kerf width and kerf depth on productivity

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).

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

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		

V. CONCLUSION

It was found that the parameters which affect the productivity in descending order are as follows: pressure (65.46%), stand off 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 (table6) was found to be pressure at range 300 Kgf/ cm^2, traverse rate at 18.41mm/sec, stand off distance at 5mm and number of passes to be 3.

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