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Optimization of Top Kerf Width produced on Graphite Filled Glass Fiber Reinforced Epoxy Composite through Abrasive Water Jet Machining

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Abstract:- Abrasive water jet machining is important unconventional machining now a day. Water jet along with abrasive particles is used to cut materials at faster rate. The various materials which can be easily cut using abrasive water jet machining are inconel, brass, composites such as epoxy, glass fiber, granite, marbles etc. The advantage of Abrasive Water Jet (AWJ) is that it can cut virtually any material. Further, it does not superheat the area adjacent to cut. The faster machining is possible. In the present work, the top kerf width of material through abrasive water jet machining has been minimized. The design variables are jet operating pressure, feed rate, stand-off distance and concentration of abrasive on kerf width produced on composite material graphite filled glass fiber reinforced epoxy. The experimental data has been taken from research work and under the practical limits of design variable are selected as realistic bounds. The minimization of kerf width has been obtained using mathematical optimization technique called Sequential Quadratic Programming (SQP). The program has been made in MATLAB. The kerf width has been minimized using above optimization method.

Keywords:- Abrasive Water Jet (AWJ) machining, Graphite Filled Glass Fiber Reinforced Epoxy, MATLAB, Sequential Quadratic Programming (SQP), Top Kerf Width (TKW)

I. INTRODUCTION

Fibre reinforced polymer composite is used in product manufacturing due to its distinct advantages such as lower weight, higher strength and stiffness, ability to mold into complex shapes, better corrosion resistance, and damping properties. In recent days, nanofillers such as graphite particles are impregnated with glass fiber reinforced polymer (GFRP) to enhance specific properties.

In AWJ machining, the machined surface does not suffer from thermal damage not only due to low heat that is generated during machining but also due to water that acts as coolant. The impacting abrasives exert smaller cutting force on the localized spots of the workpiece. Machining requires simple fixtures to support the work piece, and hence the process does not produce mechanical distortion on the cut surface.

A typical system is schematically shown in Fig-1.

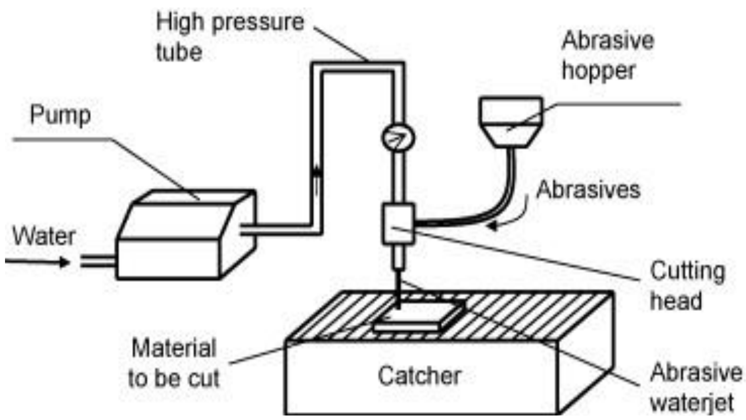

Fig- 1: A line diagram of AWJ machines [10]

Kerf is the thickness of the cut made by the jet. This is controlled by the rate at which the nozzle moves across the workpiece surface. The slower a jet nozzle moves across the material being cut, but is considerable in thick material or soft material.

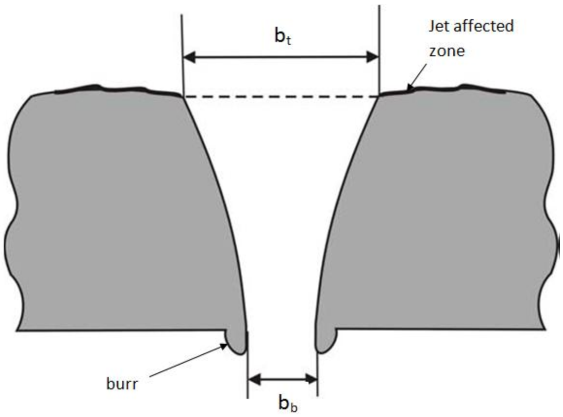

Fig- 2: A schematic diagram of AWJM kerf [11]

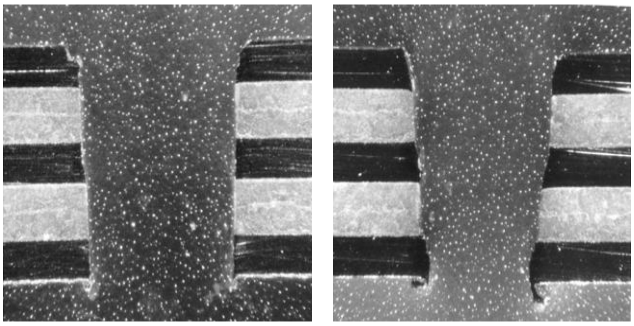

Fig-3: Photographic view of kerf (cross-section) [11]

The top of the kerf is wider than the bottom of the kerf. Generally the top width of the kerf is equal to the diameter of the AWJ. Once again, diameter of the AWJ is equal to the diameter of the focusing tube or the insert if the stand-off distance is around 1 to 5mm. The taper angle of the kerf can be reduced by increasing the cutting ability of the AWJ. Fig-2 shows the top kerf width (b_t), bottom kerf width (b_b) and jet affected zone of the material. Fig-3 shows the longitudinal section of the kerf. It may be observed that the surface quality at the top of the kerf is rather good compared to the bottom part. At the bottom there is repeated curved line formation. At the top of the kerf, the material removal is by low angle impact of the abrasive particle; whereas at the bottom of the kerf it is by plastic failure. Striation formation occurs due to repeated plastic failure.

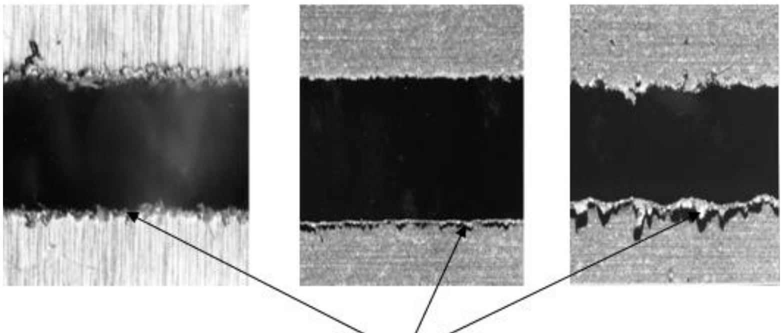

Fig-4: Photographic view of the kerf (back-side) [11]

Fig-4 shows the exit side of the kerf. Though all three of them were machined with the same AWJ diameter, their widths are different due to tapering of the kerf. Further, severe burr formation can be observed at the exit side of the kerf. Thus, in AWJM the following are the important product quality parameters.

- Striation formation
- Surface finish of the kerf
- Tapering of the kerf
- Burr formation on the exit side of the kerf.

The mechanical properties of glass/epoxy composite, namely, Young's modulus, tensile strength, flexural strength, impact strength, and wear resistance, show improvement with addition of graphite flakes. Such composites are highly suitable for manufacturing of bearing liners, gears, seals, cams, wheels, brakes, rollers, clutches, bushings, and so forth[1]. One of the major problems encountered while machining of FRP composite by traditional methods is formation of the fine dust which leads to air pollution that causes serious lung related health problems to the machine operators. In AWJ machining, the dust generated is carried away by the water jet and also no hazardous chemical is used in the process. Hence, AWJ is considered as environmentally friendly machining process. This machine tool can be effectively used for machining of FRP composites [2]. In addition to abrasive properties, machining performance is also influenced by operating parameters such as jet angle, stand-off distance (SOD), feed rate, number of cutting passes, jet pressure, abrasive flow rate, and nozzle geometry. The effect of abrasive impact angle on machining of ceramic material was investigated by Srinivasu et al. [3] using silicon carbide as abrasive.

The effect of particle shape on AWJ erosion process using silica sand abrasive. It was observed that spherical shaped or blunt edged abrasives tend to create ductile fracture with low MRR and angular shaped abrasive with sharp edges resulting in brittle fracture contributing to higher MRR [4]. The erosion rate was found to increase considerably for particle size up to 200 µm and remain constant for further increase in the particle size. Machining performance of various abrasives on glass workpiece was investigated by Khan and Haque [5]. Investigations on the effect of process parameters by Azmir and Ahsan [6] on glass fiber reinforced epoxy composites infer that abrasive hardness, operating pressure, SOD, and jet traverse rate were significant control factors which affect surface roughness and a mathematical model was developed by authors to predict. Further analysis of machined surface by Azmir and Ahsan [7] shows that at a jet angle of 90° glass fibers were found to be perfectly chopped.

A comparative analysis of AWJ machining of metals in air and in submerged conditions is made by Haghbin et al. [8]. The study shows that machining under submerged conditions produced narrower kerf than the free jet machining. In AWJ machining, the kerf profile produced depends on jet energy, jet exposure time on the workpiece, jet orientation, and material properties.

Deepak Doreswamy et al. [9] has presented the research work on, the effect of abrasive water jet (AWJ) machining parameters such as jet operating pressure, feed rate, stand-off distance (SOD), and concentration of abrasive on kerf width produced on graphite filled glass fiber reinforced epoxy composite is investigated. Experiments were conducted based on Taguchi's L_{27} orthogonal arrays and the process parameters were optimized to obtain small kerf. The main as well as interaction effects of the process parameters were analyzed using the analysis of variance (ANOVA) and regression models were developed to predict kerf width.

The present investigation is aimed to optimize top kerf width. The design variables are operating pressure, feed rate, abrasive concentration and stand-off distance on top kerf width produced on composite material graphite filled glass fibre reinforced epoxy. The experimental data has been taken from research work and under the practical limits of design variable are selected as realistic bounds [9]. The minimization of top kerf width has been obtained using mathematical optimization technique called Sequential Quadratic Programming (SQP). The program has been made in MATLAB. The top kerf width has been minimized using above optimization method.

II. SOLUTION METHODOLOGY AND NUMERICAL ANALYSIS

2.1 Solution Methodology

Solution methodology for the problem is an integration of Regression Analysis and Sequential Quadratic Programming. Regression Analysis is used to obtain top kerf width for any process parameters combination during kerf width optimization. Sequential Quadratic Programming is used for solving optimization problem.

2.2 Regression Modeling

Regression modeling is a way of expressing a model in closed form or in terms of mathematical expression or relationship. Regression analysis estimates the conditional expectations of the dependent variable given the independent variables i.e., the average value of the dependent variable when the independent variables are held fixed.

Regression methods continue to be an area of active research. In recent decades, new method have been developed for robust regression, involving correlated responses such as time series and growth curves, regressions in which the predictor or response variables are curves, images, graphs, or other complex data objects. Most common regression models are linear regression models described in the following section.

2.3 Linear Regression Model

Linear regression model is the analysis or measure of the association between one variable (the dependent variable) and one or more other variables (the independent variables), usually formulated in an equation in which the independent variables have parametric coefficients, which may enable future values of the dependent variable to be predicted or simply can be said as technique of fitting a simple equation to real data points. The most typical type of regression is linear regression constructed using the least square method (the line that minimizes the sum of the squares of the distances between the line and the data points).

Linear regression is an approach to modeling the relationship between a scalar variable y and one or more variables denoted x. In linear regression, data are modeled using linear functions, and unknown model parameters are estimated from the data. The linear regression gives the formula of the form:

$$y = a + bx \tag{1}$$

The regression model fit to a set of sample data. In general, suppose that there is a single dependent variable or response y that depends on k independent or regressor variables, for example $x_1, x_2, \ldots\ldots, x_k$. The relationship between these variables is characterized by a mathematical model called a regression model. The model ,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots\ldots + \beta_k x_k + \varepsilon \tag{2}$$

is called a linear regression model with k regressor variables. The parameters β_k, k = 0, 1,........,K, are called the regression coefficients. The parameter β_j represents the expected change in response y per unit change in x_j when all the remaining independent variables x_{iv} ($i \neq j$) are held constant.

Models that are more complex in appearance are analyzed by multiple linear regression techniques by considering an interaction between variables. For example, consider adding an interaction term to the first-order model in two variables, say

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \tag{3}$$

If we let $x_3 = x_1 x_2$ and $\beta_3 = \beta_{12}$, then above equation can be written as,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \tag{4}$$

which is a standard multiple linear regression model with three regressors.

Regression methods are frequently used to analyse data and explore the relationship between two or more variables. The model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_2 x_3 + \beta_6 x_3 x_1 + \beta_7 x_1^2 + \beta_8 x_2^2 + \beta_9 x_3^2 \tag{5}$$

is called a second order three variables regression model. The parameters β_j, j = 0, 1…, 9 are called the regression coefficients.

2.4 Estimation of the coefficients in Linear Regression Models

The model in terms of the observations, may be written in matrix notation as in equation (6),

$$y = X\beta + \epsilon \tag{6}$$

where,

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \qquad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1p} \\ 1 & x_{21} & x_{22} & \cdots & x_{2p} \\ \vdots & \vdots & & \vdots & \vdots \\ 1 & x_{n1} & x_{n2} & & x_{np} \end{bmatrix}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{bmatrix} \quad \text{and} \quad \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

y is an $(n \times 1)$ vector of the observations,

X is an $(n \times p)$ matrix of the levels of the independent variables,

β is a $(p \times 1)$ vector of the regression coefficients, and

ϵ is an $(n \times 1)$ vector of the random errors.

Thus least square estimator of β is given in equation (7),

$$\beta = (X^{'}X)^{-1}X'y \tag{7}$$

The regression coefficients of linear regression model are obtained by solving equation (7). Finally regression model is obtained by putting these coefficients in equation (6).

2.5 Optimization Technique

Optimization is necessary for the control of any process to achieve better product quality, high productivity with low cost. In this work optimization based on available model has been carried out to obtain optimum parameters via Sequential Quadratic Programming (SQP) based on the objective of minimizing of total cost and total cycle time.

2.5.1 Overview of Sequential Quadratic Programming optimization Method

SQP methods represent the state of the art in nonlinear programming methods. The sequential quadratic programming is one of the most recently developed and perhaps one of the best methods of optimization. The method has a theoretical basis that is related to:

(1) The solution of a set of nonlinear equations using Newton's method and

(2) The derivation of simultaneous nonlinear equations using Kuhn–Tucker conditions to the Lagrangian of the constrained optimization problem.

Schittkowski for example, has implemented and tested a version that outperforms every other tested method in terms of efficiency, accuracy, and percentage of successful solutions, over a large number of test problems. This method allows to closely mimic Newton's method for constrained optimization just as is done for unconstrained optimization. At each major iteration, an approximation is made of the Hessian of the Lagrangian function using a quasi-Newton updating method. This is then used to generate a QP sub problem whose solution is used to form a search direction for a line search procedure. The general method, however, is stated here.

The principal idea is the formulation of a QP sub problem based on a quadratic approximation of the Lagrangian function which is given in equation 3.12,

$$L(x,\lambda) = f(x) + \sum_{i=1}^{m} \lambda_i \cdot g_i(x) \tag{8}$$

Here we simplify equation-3.12 by assuming that bound constraints have been expressed as inequality constraints. We obtain the QP sub problem by linearzing the nonlinear constraints.

Quadratic Programming (QP) Sub problem is given in equation (9),

$$min \frac{1}{2}\, d^T H_k d + \nabla_f\, (x_k)^T\, d$$

$$\nabla g_i\, (x_k)^T d + g_i\, (x_k) = 0, \qquad i = 1,2, \ldots \ldots \ldots, m_e$$

$$\nabla g_i\, (x_k)^T d + g_i\, (x_k) \leq 0, \qquad i = m_e + 1, \ldots \ldots \ldots, m \tag{9}$$

This sub problem can be solved using any QP algorithm. The solution is used to form a new iterate

$$x_{k+1} = x_k + a_k d_k.$$

The step length parameter α_k is determined by an appropriate line search procedure so that a sufficient decrease in a merit function is obtained , The matrix H_k is a positive definite approximation of the Hessian matrix of the Lagrangian function , H_k can be updated by any of the quasi-Newton methods, although the BFGS method appears to be the most popular.

A nonlinearly constrained problem can often be solved in less iteration than an unconstrained problem using SQP. One of the reasons for this is that, because of limits on the feasible area, the optimizer can make informed decisions regarding directions of search and step length.

2.6 Numerical Analysis

The analysis of variance (ANOVA) results are evaluated for abrasive water jet machining. The numerical data of kerf width minimization of process parameters of abrasive water jet machining for 27 combinations of design variables. The same data has been taken for testing and for comparison purpose. The methodology suggested in the present work table 1 show the required data [9]. Regression coefficients are obtained performing regression analysis of the salon date. The analysis is presented in sub section 2.6.1 and the minimization of top kerf width is performed in section 2.6.2.

2.6.1 Computation of Regression Coefficients

Data of design parameters forms the input matrix represented by [X] and safety factor forms the vector of observations by *y* for regression analysis.

For this problem, matrices of eqn. (6) such that *k*=14, *n*-27 are given below

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \qquad x = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1p} \\ 1 & x_{21} & x_{22} & \cdots & x_{2p} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{n1} & x_{n2} & & x_{np} \end{bmatrix} \quad \text{and} \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \\ \beta_6 \\ \beta_7 \\ \beta_8 \\ \beta_9 \\ \beta_{10} \\ \beta_{11} \\ \beta_{12} \\ \beta_{13} \\ \beta_{14} \end{bmatrix}$$

where,

y is an (27×1) vector of the observations,

X is an (27×14) matrix of the levels of the independent variables,

β is a (14×1) vector of the regression coefficients, and

ϵ is an (27×1) vector of the random errors.

Table 1: Data for kerf width minimization design variables [9]

S. No.	Design variables				Average response values	
	Operating pressure (MPa), x_1	Feed rate (mm/min), x_2	Abrasive concentration (wt.%), x_3	SOD (mm), x_4	TKW(mm)	BKW(mm)
1	90	75	6	1	0.845	0.803
2	90	75	10	3	0.905	0.892
3	90	75	14	5	0.964	0.936
4	90	100	6	3	0.896	0.853
5	90	100	10	5	0.950	0.912
6	90	100	14	1	0.847	0.827
7	90	125	6	5	0.870	0.835
8	90	125	10	1	0.823	0.816
9	90	125	14	3	0.860	0.850
10	120	75	6	3	0.960	0.913
11	120	75	10	5	1.176	1.150
12	120	75	14	1	0.890	0.868
13	120	100	6	5	1.104	1.055

14	120	100	10	1	0.875	0.845
15	120	100	14	3	0.981	0.977
16	120	125	6	1	0.855	0.803
17	120	125	10	3	0.917	0.852
18	120	125	14	5	0.987	0.935
19	150	75	6	5	1.203	1.155
20	150	75	10	1	0.938	0.918
21	150	75	14	3	1.052	1.005
22	150	100	6	1	0.903	0.872
23	150	100	10	3	0.965	0.887
24	150	100	14	5	1.150	1.015
25	150	125	6	3	0.892	0.880
26	150	125	10	5	1.065	0.992
27	150	125	14	1	0.882	0.871

Regression coefficient obtained by putting x and y in eqn.(7) are as follows:

$$\beta = \begin{bmatrix} 0.086900 \\ 0.008700 \\ 0.006000 \\ -0.010000 \\ 0.000050 \\ -0.000020 \\ 0.000100 \\ 0.000600 \\ 0.000100 \\ -0.000600 \\ -0.000500 \\ -0.000030 \\ -0.000023 \\ -0.000300 \\ 0.006500 \end{bmatrix} \qquad (10)$$

The regression equations generated after putting these regression coefficients in eqn. (5) is given below,

$$y = 0.086900 + 0.008700\, x_1 + 0.006000\, x_2 - 0.010000\, x_3 + 0.000050\, x_4 - 0.000020\, x_1x_2 + 0.000100\, x_1x_3 + 0.000600\, x_1x_4 + 0.000100\, x_2x_3 - 0.000600\, x_2x_4 + 0.000500\, x_3x_4 - 0.000030\, x_1^2 - 0.000023\, x_2^2 - 0.000300\, x_3^2 + 0.006500\, x_4^2 \qquad (11)$$

2.6.2 Minimization of top kerf width

The optimization problem may now be stated as,

Minimize $f(x) = 0.086900 + 0.008700\, x_1 + 0.006000\, x_2 - 0.010000\, x_3 + 0.000050\, x_4 - 0.000020\, x_1x_2 + 0.000100\, x_1x_3 + 0.000600\, x_1x_4 + 0.000100\, x_2x_3 - 0.000600\, x_2x_4 + 0.000500\, x_3x_4 - 0.000030\, x_1^2 - 0.000023\, x_2^2 - 0.000300\, x_3^2 + 0.006500\, x_4^2$

Subjected to $90 \leq x_1 \leq 150$ (12)

$75 \leq x_2 \leq 125$ (13)

$6 \leq x_3 \leq 14$ (14)

$1 \leq x_4 \leq 5$ (15)

The resulting optimization problem is to minimize objective function under constraints equations (12), (13), (14) and (15). The problem is solving using Sequential Quadratic Programming. MATLAB is used for this purpose. The solution of the problem begins with the selection of Sequential Quadratic Programming in the solver pane of optimization toolbox of MATLAB. The objective functions equation (10) of optimization problem is M-file entered in fitness function pane of toolbox in form @objfun. The M-file of the problem is made in following format:

function [y] = objfun (x)
$y = 0.086900 + 0.008700\, x_1 + 0.006000\, x_2 - 0.010000\, x_3 + 0.000050\, x_4 - 0.000020\, x_1x_2 + 0.000100\, x_1x_3 + 0.000600\, x_1x_4 + 0.000100\, x_2x_3 - 0.000600\, x_2x_4 + 0.000500\, x_3x_4 - 0.000030\, x_1^2 - 0.000023\, x_2^2 - 0.000300\, x_3^2 + 0.006500\, x_4^2$
output args=y;
end

Lower and upper bounds given in equation (12), (13), (14) and (15) are fed in the bounds pane in following format:

Lower: [90, 75, 6, 1]
Upper: [150, 125, 14, 5]
Starting points for SQP problem has been taken [95, 85, 10, 1]

III. RESULTS

The optimization problem is solved by using Sequential Quadratic Programming tool box of MATLAB and optimum results are shown in table 2.

Table II: Result of top kerf width

Kerf width (mm)	Operating pressure (MPa), x_1	Feed rate (mm/min), x_2	Abrasive concentration (wt.%), x_3	SOD (mm), x_4	y_{TKW} (mm)
Optimum (modified design) values	$x_1^*=90$	$x_2^*=75$	$x_3^*=10$	$x_4^*=1$	0.86405

Parameters such as operating pressure, feed rate, abrasive concentration and stand-off distance after optimization are $x_1^*=90$, $x_2^*=75$, $x_3^*=10$ and $x_4^*=1$. Thus, top kerf width reduction is 0.86405 mm.

IV. DISCUSSION

A comprehensive methodology for minimization of top kerf width for abrasive water jet machining is presented. The experimental data first taken from the paper [9] is used to generate the regression equation with given four input variables in MATLAB. The input variables taken are operating pressure, feed rate, abrasive concentration, stand-off distance. The range of parameter is identified. The upper and lower bounds are determined. Then the objective function is optimized by sequential quadratic programming method in MATLAB command window and the optimized tool box of MATLAB. Thus the result is generated which gives us the minimum value of top kerf width is 0.86405 mm and the optimum values of input parameters are: operating pressure is 90 MPa, feed rate is 75 mm/min., abrasive concentration is 10 wt%, stand-off distance is 1 mm. Thus, the above optimization function decreases the top kerf width. Therefore, overall productivity of the machining operation will increase.

Therefore by this method the abrasive water jet machining techniques efficiency and productivity increased. This method can also be used in many areas of conventional and non-conventional machining techniques because of its simple methodology and fast convergence to the optimum point.

V. CONCLUSIONS

In the present work top kerf width minimization has been achieved. First of all top kerf width has been solved related to four parameters operating pressure, feed rate, abrasive concentration and stand-off distance using regression analysis. The equation thus obtained is minimized under practical bounds of above mention parameters. Minimization of top kerf width has been achieved using SQP method. The following conclusions are made:

1. The optimization method successfully minimizes the top kerf width.
2. The contribution of stand-off distance is less significant.
3. With typical orifice diameters, abrasive water jet kerf width is kept to a minimum, thus maximizing material utilization.

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