

# Genetic Algorithm Based Optimization of Material Removal Rate of Abrasive Waterjet Cutting of Polymer Composites

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## Abstract

In this paper an empirical model for material removal rate (MRR) of abrasive waterjet (AWJ) cutting of polymer matrix composites has been developed based on experiment conducted. The MRR is optimized using Genetic Algorithm (GA) for the carbon/epoxy reinforced composite with a constraint on surface roughness. The GA based approach on varying the process parameters, gives maximum value of MRR.

**Keywords:** Abrasive waterjet cutting, Material removal rate, Genetic algorithm, Design of experiment.

## 1 Introduction

Machining of composites by traditional methods like drilling, EDM, laser beam cutting etc. has many disadvantages. One of these is that almost all the traditional machining processes involve the dissipation of heat into the workpiece. This serious shortcoming has been overcome by jetting technologies. Hence there has been a great interest for improving the machining of composite materials, particularly in the aerospace industry. However the selection of optimum process parameters for abrasive waterjet (AWJ) cutting of any material is based on certain objectives such as cutting the material to any predetermined depth or cutting the material with a certain quality of cut. This requires an elaborate experimentation. To avoid the time consuming experimentation, researchers adopted different approaches such as design of experiments, semi-empirical approaches and analytical procedures [1]. In this paper an empirical model is developed for the material removal rate (MRR) of AWJ cutting of polymer matrix composites based on experimental data. The MRR is maximized using Genetic algorithm (GA) with constraints on surface

fibres in the upper cutting region, but the fibres are mostly pulled out in the lower region, depends on the level of particle energy [2]. Hence, it is not appropriate to use either the erosion theories [3, 4] or the fracture mechanics approach to model the AWJ cutting process for polymer matrix composites.

### Nomenclature

C	system constant
$d_o$	jet diameter
$d_m$	mixing tube diameter
$f_a$	abrasive factor
h	depth of cut
K	constant
MRR	material removal rate
$m_a$	abrasive flow rate
$n_1, n_2, n_3, n_4$	constants
$N_m$	Machinability number
$O_c$	orifice coefficient
$P_w$	pressure
q	quality level
$R_a$	surface roughness
U	traverse speed

## 2 Material Removal Rate Model

Cut surface of Polymer Matrix Composite using AWJ reveals that the erosive process for the matrix material (resin) involves shearing and ploughing as well as intergranular cracking. Shearing or cutting was found to be the dominant process for cutting the

An empirical approach was used to develop the model based on the experimental data. The material removal rate can be calculated by multiplying the cross-sectional area of the cutting front by the jet traverse rate  $U$ . By assuming the variation of the kerf width along the depth is uniform, rate of material removed can be given by  $MRR=hUW$  ----- (1)

Where,  $h$  is depth of cut and  $W$  is kerf width. To achieve the requisite depth at a particular traverse speed and instead of measuring kerf width each time, traverse speed and kerf width can be defined in terms of process parameters. Further the traverse speed and kerf width are combined in Equation 1, to obtain the MRR in terms of process parameters. Thus the kerf width and traverse speed becomes: **Kerf Width**

Kerf width is related to the “effective” jet diameter within which the particle energy is above the threshold value for removing the target material, this in turn dependent on the jet energy (or water pressure) and energy distribution within the jet as well as the material destructive energy [5]. Further kerf width increases approximately linearly with water pressure as greater the water pressure results in greater jet kinetic energy impinging on the material and opens a wider slot [6], also to some extent with an increase in the abrasive mass flow rate; however, this increase is not in a linear form since the cutting efficiency of individual particles decreases with an increase in the mass flow rate owing to the increased interference between particles [7] and decreases with an increase in traverse speed because of faster passing of jet allows fewer abrasive to strike on the jet target and hence generate a narrow slot [7]. Thus, the kerf width may be expressed in the following empirical form:

$$W=Kd_o \frac{m_a^{n1}P_w^{n2}}{U^{n3}} \quad (2)$$

Where,  $m_a$  is abrasive mass flow rate,  $P_w$  is waterjet pressure,  $d_o$  is jet diameter, and  $K$ ,  $n1$ ,  $n2$ ,  $n3$  and  $n4$  are constants.

**2.1 Traverse Speed and Depth of cut**

Various attempts had been made in order to maintain or predict the depth of cut. Workpiece normal force generated by an abrasive waterjet used as the indicator of the depth of jet penetration and that a force-feedback control as an effective way to regulate the depth of jet penetration [8]. However selection of AWJ process parameters for a required depth of cut in a given material was effectively done by applying

the principle of fuzzy set theory [9]. In this study the traverse speed at which the requisite depth of cut at the desired quality was maintained by using the machinability number equation [12]. The advantage of using this equation is that once the machinability number of a given material is known, traverse speed can be predicted as an application of machinability number for the desired depth of cut and by properly selecting the value of process parameters for the requisite quality. The traverse speed can be written by using the machinability number as follows:

$$U=O_c \left( \frac{f_a N_m P_w^{1.594} d_o^{1.374} m_a^{0.343}}{C q h d_m^{0.618}} \right)^{1.15} \quad \text{----- (3)}$$

Where,  $f_a$  is abrasive factor,  $N_m$  is machinability number,  $C$  is system constant,  $q$  is quality level,  $d_m$  is mixing tube diameter,  $O_c$  is orifice coefficient.

**3 Surface Roughness model**

In general it has been found that surface roughness increases with an increase in water pressure and traverse speed [6] and found to be significant with increasing depth of cut [13]. However high supply pressure and corresponding low values of traverse speed are necessary choice for high surface quality when machining thick laminate specimens [14]. Hence the surface roughness ( $R_a$ ) can be written in the following empirical form:

$$R_a =x1 \frac{m_a^{x2}P_w^{x3}}{U^{x4}} \quad \text{----- (4)}$$

Where,  $x1$ ,  $x2$ ,  $x3$  and  $x4$  are constants.

**4 Experimentation**

The experiments were performed on a OMAX 2652 AWJ machine [15]. It has a precision X-Y table for the movement of cutting head, hopper attached with cutting head to feed the abrasive and a controller and a pump to maintain the jet pressure of 380 Mpa. In this study Carbon/Epoxy (Volume fraction 46%) reinforced composite of thickness 2 mm is used as the workpiece material having machinability number 425 [16]. AWJ cutting involves large no of cutting variables [17] and practically all these variables affect the cutting results. In this study only easy to adjust variables are considered. The selected variables are pressure, abrasive flow rate and quality level. Based upon a three levels, three factor, full factorial experimental design, 27 through cuts of 50 mm had been produced for evaluation [18]. Water

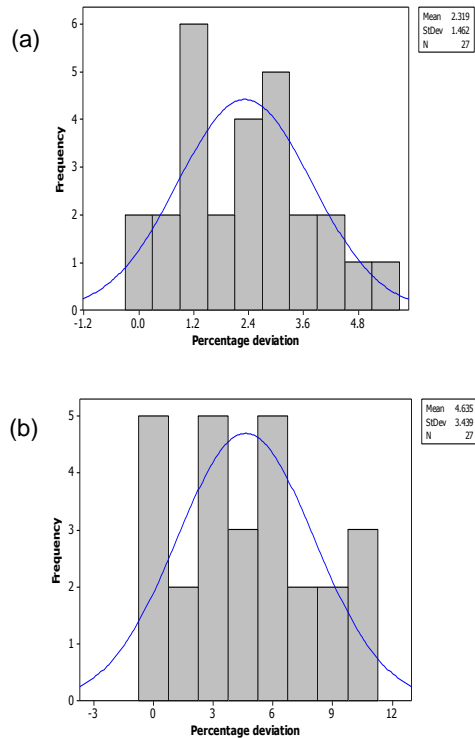
pressure is selected as 2500, 3000 and 3500 Pa, abrasive flow rate as 250, 335 and 400 gm/min and quality level as 3, 4 and 5. Quality level stands for the quality of the upper 1/q section of a separation cut surface. High quality level results in slow cutting speed [12]. Quality level 3 stands for smooth cutting zone with striation marks, 4 stands for striation free zone and 5 stands for very smooth cutting zone. Rest all other parameters was kept constant as per the machine standard configuration, that is nozzle orifice diameter 0.3556 mm, mixing tube diameter 0.762 mm, stand off distance 2 mm, orifice coefficient 0.7 and abrasive factor 1. The abrasive used was almandite garnet sand with a mesh number of 80. The cut surface's roughness was measured using a Taylor-Hobson Subtronic 10 stylus profilometer and kerf width with the help of Bausch and Lomb shadowgraph. To obtain the coefficients of Equation (2) and (4), nonlinear regression analysis had been carried out on NLREG program [19]. Hence the kerf width and surface roughness becomes:

$$W = 1.1737 d_o \frac{m_a^{0.02} P_w^{0.1847}}{U^{0.03146}} \quad \text{--- (5)}$$

$$R_a = 85.87 \frac{m_a^{0.1808} P_w^{-0.78807}}{U^{-0.1178}} \quad \text{----- (6)}$$

### 5 Assessment of the equations

In order to check the adequacy of the equations, a comparison has been carried out based on the percentage deviation of the model predicted value with respect to the corresponding experimental result. This is shown in the histogram in Fig.1a and Fig. 1b. This comparison shows that the model's prediction yields an average percentage deviation of 2.39% with the standard deviation of 1.462% for Equation 5, (Fig. 1a) and an average percentage deviation of 4.635% with the standard deviation of 3.439% for Equation 6, (Fig. 1b).



**Figure1:** Percentage deviation of model prediction for (a) Kerf width  $W$  (b) Surface roughness  $R_a$

### 6 Material removal rate

The material removal rate (MRR) obtained by putting Equation (5) and (3) in Equation (1) and solving it is:

$$MRR = \frac{1.1737 O_c h^{-0.15} P_w^{2.0178} d_o^{3.524} m_a^{0.4145}}{U^{0.03146}} \left( \frac{f_a N_m}{C q d_m^{0.618}} \right)^{1.15} \quad \text{--- (7)}$$

### 7 Optimization by genetic algorithms

#### 7.1 Introduction to Genetic Algorithms

Genetic Algorithms are search algorithms for optimization, based on the mechanics of natural selection and genetics [20]. The power of these algorithms is derived from a simple heuristic assumption that the best solution will be found in the regions of solution space containing high proportion of good solution, and that these regions can be identified by judicious and robust sampling of the solution space. The mechanics of GAs is simple, involving copying of binary strings and the swapping of the binary strings. The computations are carried out in three stages to get a result in one generation or

iteration. The three stages are (a) Reproduction (b) Cross-over (c) Mutation [18].

**7.1.1. Reproduction**

The primary objective of the reproduction operator is to make duplicates of good solutions and eliminate bad solutions in a population, while keeping the population size constant. This can be achieved by identifying the good solution in a population, make multiple copies of good solutions and eliminating bad solutions from the population so that multiple copies of good solutions can be placed in the population.

**7.1.2. Crossover**

A crossover operator is applied next to the strings of the mating pool. Two strings are picked from the mating pool at random and some portion of the strings are exchanged between the strings at the crossover site to create two new strings.

**7.1.3. Mutation**

The mutation operator is also used for the search aspect of GA. The bitwise mutation operator changes a 1 to 0 and vice versa, with the mutation probability.

**7.2 Optimization of MRR**

The problem of optimization of AWJ cutting process can be described as maximizing MRR subject to a certain set of constraints on surface roughness and input variables. In order to use GA, the constrained optimization problem is stated as follows:

Maximize MRR

Subject to,  $R_{a_{min}} \leq R_a \leq R_{a_{max}}$

$X_i^l \leq X_i \leq X_i^u$

Where,  $X_i^l$  and  $X_i^u$  are the lower and upper bounds on process variables  $X_i$ .

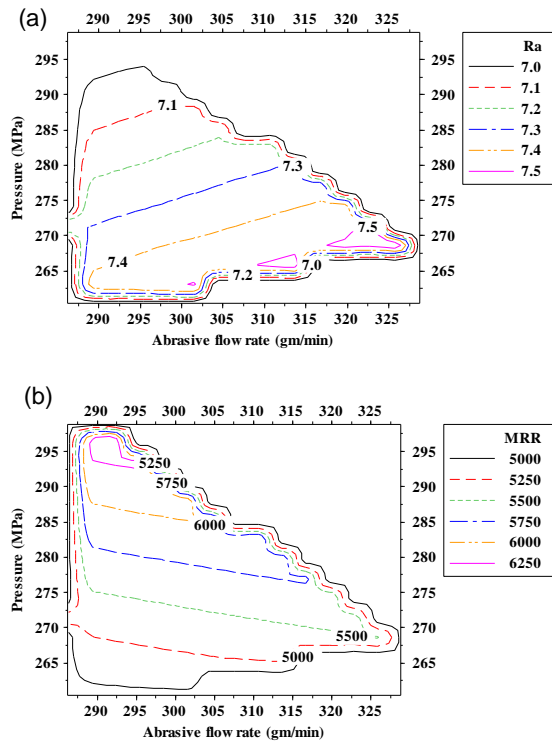
The GA code was developed in Matlab 6.5.

**8 Result and discussion**

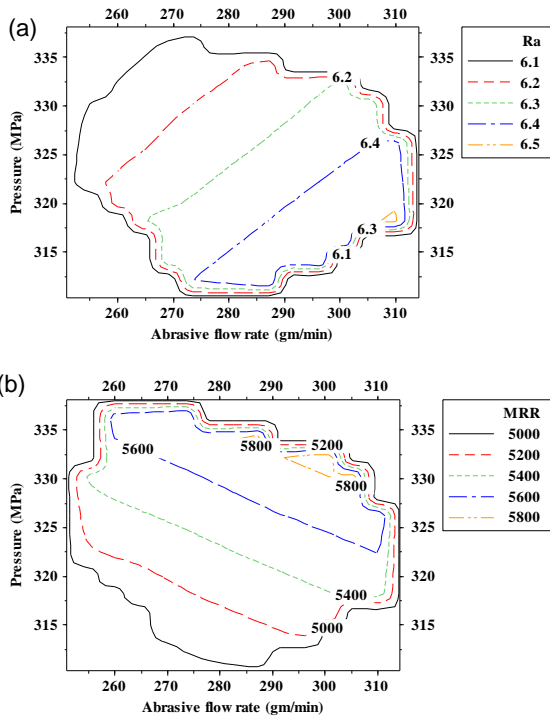
In the present case of optimization of AWJ cutting process, objective function which is material removal rate to be maximized subjected to constraint on surface roughness. According to the machine and the workpiece limits, the constraints on input variables

Pressure (MPa) and abrasive flow rate (gm/min) are  $250 \leq P_w \leq 350$  and  $250 \leq m_a \leq 400$  respectively.

The following parameters were used in the GA runs, to get the optimal solution: population size 20, maximum number of generations 500, string length is 1023, crossover probability is 0.8 and mutation probability is 0.01. The MRR equation was optimized using Genetic Algorithm. Simulation was carried out for a particular quality level. The input cutting parameters were fed to the GA program. The GA program uses different types of crossover and mutation operators to



**Figure 2:** Contour plot for (a) Surface roughness 7-7.5  $\mu$  (b) MRR at quality level 3



**Figure 3:** Contour plot for (a) Surface roughness (a 6-6.5  $\mu$ ) (b) MRR at quality level 4

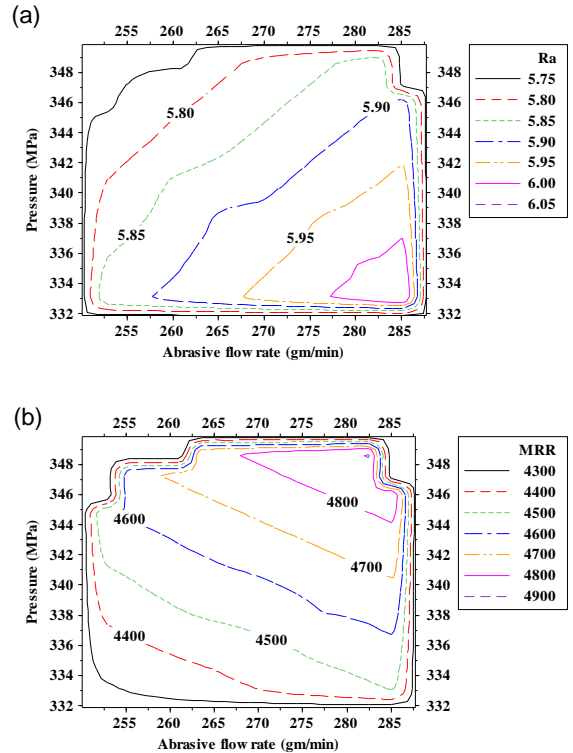
predict maximum values of material removal rate with constraint over surface roughness. This approach provides optimum cutting conditions for corresponding, maximum material removal rate. This gives the range of material removal values for a certain range of machining parameters. Figure. 2a and 2b shows the material removal rate and surface roughness contour plot at quality level 3 with constraint over roughness in the range of 7-7.5  $\mu$ . The maximum and minimum values of material removal rate was 5000, 6000  $\text{mm}^3/\text{min}$  for the constraint over the roughness 7-7.5  $\mu$ .

Similarly, Fig. 3a and 3b shows the material removal rate and surface roughness contour plot at quality level 4 with constraint over roughness in the range of 6-6.5  $\mu$ . The maximum and minimum values of material removal rate was 5000, 5800  $\text{mm}^3/\text{min}$  for the constraint on the roughness 6-6.5  $\mu$ . Figure. 4a and 4b shows the material removal rate and surface roughness contour plot at quality level 5 with constraint over roughness in the range of 5.5-6  $\mu$ . The maximum and minimum values of material

removal rate was 4400, 4800  $\text{mm}^3/\text{min}$  for the roughness constraint of 5.5-6  $\mu$ .

### 9 Conclusions

An optimized empirical model for the material removal rate of abrasive waterjet cutting of polymer matrix composite has been developed here using GA which result in obtaining the optimal process parameters by maintaining the requisite surface quality. The predicted optimal process parameters and surface roughness at which the maximum MRR is obtained, closely matches the experimental results. Application of GA based approach to obtain optimal cutting conditions is likely to be very useful at the Computer Aided Process Planning (CAPP) stage in a production setup. Further this model can be optimized by including the another constraints as taper angle.



**Figure 4:** Contour plot for (a) Surface roughness (a 5.5-6  $\mu$ ) (b) MRR at quality level 5

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