Optimization of Specific Energy Consumption in Turning of GFRP Composites using Particle Swarm Optimization

Syed Altaf Hussain, Palani Kumar.K, Md.Alamgir

Abstract*: In this paper, an attempt is made to optimize the control parameters for the minimization of specific energy consumption in turning GFRP composites using particle swarm optimization (PSO).Optimization of specific energy consumption in machining is helpful to evaluate the process energy characteristics and also facilitates choosing the best control parameters for energy saving. The control parameters considered are cutting speed, feed, depth of cut and fiber orientation angle. Experiments are planned and executed according to Taguchi's L_{25} orthogonal array in the design of experiments on an all geared lathe with PCD cutting tool insert. A quadratic predictive model was developed for specific energy consumption using RSM and the optimal combinations of control parameters were determined using PSO. The Predicted results from PSO show that there is an improvement in MRR by 46.44% and a reduction in SEC by 33.69%. From the confirmative experimental results, it is observed that PSO algorithm has a powerful global search ability to solve the optimization problem.

Keywords: GFRP Composites, Taguchi Method, Turning, Specific Energy Consumption, PCD Tool Insert, Particle Swarm Optimization (PSO)

I. INTRODUCTION

GFRP composites are widely used in a variety of engineering applications because of their superior properties over conventional materials. The tailorability of composites for definite application has been one of their greatest advantages and it is the most prominent factor for adopting them as an alternative to conventional materials. Machining is one of the most economically viable processes in manufacturing industries [1, 2]. The economic objective of the machining process depends on the optimization of control parameters to achieve high-quality standards [3]. The study of the specific cutting energy consumption which is defined as the energy required for removing one unit volume of material per unit time is the gateway to understand the electrical energy utilization in the machining process. The specific energy can also be used as an indicator for evaluating the sharpness of the cutter, design of the machine tool electric motor. The estimation of specific energy based on a machine tool, material characteristic and process variables are classified into three categories namely empirical, analytical and mechanistic methodology [4]. Few researchers [5], [6], and [7] proposed methodologies to estimate and model the specific energy consumption through mechanistic modeling and experimental analysis.

These approaches critically investigated the specific energy and recommended input parameters to optimize the electrical energy demand during machining. Estimated that two-thirds of the electrical energy used by the machining industry is meant for running motors and drives for cutting tools[8]. The total cost of energy used over ten years is about 100 times higher than the initial purchase cost of the machine tools used to manufacture products [9]. Yu su [10] applied Grey relational analysis approach for multi-response optimization in turning of AISI304 austenitic stainless steel. Pengfei Hu [11] demonstrated that PSO algorithm based on the desirability function has the powerful global search ability and high convergence to solve the optimization problem. Panda [12] applied Grey Relational Analysis (GRA) and modified PSO for multi Response characteristic optimization of EDM Process. Arindam Majunder [13] have optimized the EDM process parameters using desirability based multi-objective PSO. Bobby Oedy [14] applied back propagation neural network-particle swarm optimization (BPNN-PSO) for multi-Response optimization in the drilling of carbon fiber reinforced polymer (CFRP) composites. Azmi [15] studied the effect of machining parameters on specific energy consumption in turning of CFRP composites, experimental evidence shows that minimum specific energy consumption was noticed at higher feed rates. Marathe and Javali [16] reported the effect of machining parameters on the specific energy and delamination damage of glass fibre reinforced polyester composites in the drilling operation. The experimental result reveals that feed rate was the main factor that lowers the cutting energy per unit volume or metal removal. Rosario [17] studied the energy required during the dry drilling of PEEK GF30 (polyetheretherketone) reinforced with glass fiber. ANOVA showed that the type of drill is a more influential factor and the optimum conditions are with the tool made of tungsten carbide with a diamond point at high cutting speeds and feed rate. From the literature review, it is understood that no comprehensive work was carried out in understanding the effects of process parameters on the specific energy consumption in turning of GFRP composites.

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Therefore,before machining a part or component the optimum energy consumption per unit volume of the machined product should be determined to improve profit, reduce the operating cost and minimize the environmental impact generated from the energy production of manufacturing firms. Specific energy consumption in this study is considered as an energy-efficient indicator to minimize the energy intensity of a given machined product.

II. MATERIALS AND METHODS

The work material used for the present study is GFRP composite tubes of different fiber orientation angles, whose angle varies from 30°~90° in steps of 15°. The inner and outer diameter of the tube is 30mm and 60mm, the length of the tube is 500mm. The tubes used in this investigation are manufactured by the filament winding process. The fiber used in the tube is E-glass and the resin used is epoxy. The fiber orientation angle on the tubes is set during manufacturing by the filament winding process. The photograph of the material used is shown in Figure 1 and the specification of the materials used is given in Table 1.

Fig.1 GFRP Tubes of different fiber orientation

Table 1. Specifications of fiber and resin

Fiber : E-Glass – R099 1200 P556	Resin : Epoxy
Manufacturer : Saint Gobain vetrotex India Ltd.	Manufacturer:: CIBA GEIGY
R099- Multi filament Roving	Product: ARALDITE MY 740 IN
1200- Linear Density, Tex	110 KG Q2
P556-Sizing reference for vetrotex	Hardener : HT 972

A. Experimental Details

The experimental runs are conducted according to Taguchi's L_{25} orthogonal array [18] in the DOE, which helps in reducing the number of experiments. The control parameters considered in this study are cutting speed (V), feed (f), Depth of cut (d) and fiber orientation angle (Φ). Since all the considered control parameters are multi-level variables and their outcome affects are not linearly related. The control parameters and their levels are shown in Table 2. All the GFRP tubes are turned on an all-geared lathe of model NAGMATI-175. The ISO specification of the tool holder used for the turning operation is WIDAX tool holder PC LNR 2020 K12 and the tool insert is PCD of type CNMA 120408. During machining, the cutting force developed was measured using a KISTLER quartz 3-component dynamometer. The schematic layout of the experimental setup is shown in Figure 2.

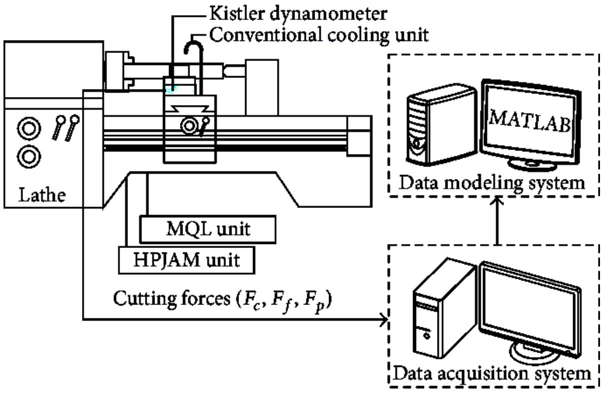

Fig. 2 Schematic layout of Experimental setup.

Table 2. Control Parameters and their levels.

Control parameter with units	Notation	Levels 1	2	3	4	5
Cutting speed, m/min	V	40	60	95	145	225
Feed, mm/rev	f	0.048	0.096	0.143	0.191	0.238
Depth of Cut, mm	d	0.25	0.5	0.75	1.0	1.25
Fiber orientation angle,deg	Φ	30	45	60	75	95

Cutting power in each experimental run was recorded and the Specific Energy Consumption is calculated using Eq.(1).

$$SEC = \frac{Cuttingpower}{MRR} = \frac{P}{Vfd} \quad (\text{J/mm}^3) \qquad (1)$$

B. Response Surface Methodology (RSM)

Taguchi S/N ratio is a statistical measure of performance or quality for data analysis and prediction of optimal parameters setting [20]. The S/N ratio is the ratio of the mean signal to the standard deviation (Noise). It depends on the quality characteristics of the process to be optimized. The standard S/N ratios generally used Nominal-is-Best (NB), Lower-the-better (LB) and Higher-the-Better (HB). In this investigation, MINITAB-18 was used to solve the optimization problem. Specific energy consumption was taken as LB characteristic, aimed at minimizing the response. The LB-S/N ratio was computed using Eq.(4)

$$S/N = -10\log\frac{1}{n}\sum_{i=1}^{n} y_i^2 \qquad (4)$$

C. Particle Swarm Optimization (PSO)

PSO is a global optimization technique that has been developed by Kennedy and Eberhardt [21]. PSO is a swarm intelligence meta-heuristic inspired by the group behaviour of animals, i.e., bird flocks or fish school. Similar to a genetic algorithm (GAs), it is a population-based method. It represents the state of an algorithm by a population, which is iteratively modified until a termination criterion is satisfied. In PSO algorithms, the population P=[p_1…. p_n] of the feasible solution is often called a swarm.

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The feasible solution $P_{,}$.......P_n is called particles. For solving practical problems the number of particles is usually chosen between 10 and 50. Thus, a PSO algorithm can be employed to solve an optimization problem.

Each particle changes its direction based on the additional components towards its best solution 'P best' and towards the overall best position 'g best'. The PSO considers a swarm *S* containing *n* particles (s = 1, 2…...n) in a *d*-dimensional continuous solution space. The position and velocity of individual s_i are represented as the vectors xi = (x^{i1}………x^{id}) and vi = (v^{il}………..v^{id}), respectively. A bird adjusts its position to find the best position, according to its own experience and the experience of its companions. Using the information, the updated velocity of individual *i* is modified using Eq. (5).

$$v_i^{k+1} = w \times v_i^k + c_1 \times r_1 \times \left(P_{besti} - x_i^k\right) + c_2 \times r_2 \times \left(g_{best} - x_i^k\right)$$

(5)

$$x_i^{k+1} = x_i^k + \chi \times v_i^{k+1}$$

Where

v_i^{k+1}	=	i[th] particle velocity for (k+1) iteration
w	=	Particle inertia weight
v_i^k	=	i[th] particle for k iteration
c_1, c_2	=	Constants c_1, c_2 ε [0, 0.25]
r_1, r_2	=	Numbers generated randomly between [0,1]
P_{besti}	=	i[th] particle best position depend on its experience
x_i^k	=	i[th] particle position for k[th] iteration
g_{best}	=	Particle global best position in population
x_i^{k+1}	=	i[th] particle position for (k+1)[th] iteration
χ	=	Factor of construction

Control parameters of PSO

Number of generations = 75
Number of particles (N) =4
c_1 = 1.6
c_2 = 2
w = 1.0
Coding of particle = binary
Number of bits per parameter is taken as 4.
Number of significant parameters = 4
Total length of particle = 12
Fitness parameter: minimization of Specific energy consumption

A flow chart of PSO for optimization of specific energy consumption (SEC) in turning of GFRP Composites is shown in figure 3.

Particle swarm optimization (PSO) was implemented using MATLAB (R2020b) software package.

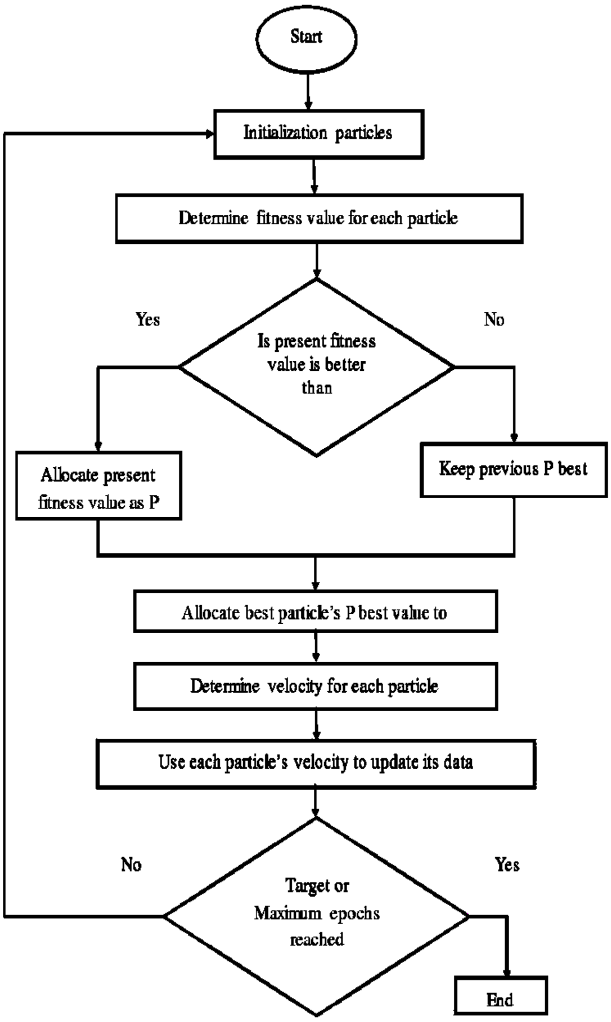

Fig. 3 Flow chart of PSO

III. RESULTS AND DISCUSSION

Experiments are planned executed on an all geared lathe machine according to L_{25} orthogonal array in DOE and the results obtained are shown in Table 3.

The MINITAB-18 Software was used to develop the SEC (Specific energy consumption) model in terms of control viz., V, f, d and Φ is shown in Eq.(6)

$$SEC = 38.26 - 0.0568V - 136.9f - 34.38d - 0.153\Phi + 0.00000V*V + 205f*f + 10.52d*d + 0.00036\Phi*\Phi + 0.154V*f + 0.0005V*d + 0.000441v*\Phi + 41.7f*d - 0.03f*\Phi + 0.093d*\Phi \quad (6)$$

In the quadratic model shown in Eq. (6), insignificant terms are included in order to increase the prediction capability

A. Analysis of Variance for the SEC Model

The experimental results are analyzed with ANOVA to identify the factors that significantly affect the performance measure on the total variance of the results. The ANOVA is carried out at α=0.05 significance level (95%) confidence level) gave results are SEC shown in Table 4. The sources with P-value < 0.05 are considered as highly statistically significant.

Table 3. Experimental results for SEC and S/N

Exp.No	V (m/min)	F (mm/rev)	d (mm)	(Φ) degree	P (W)	MRR (mm^3/s)	SEC (J/mm^3)	S/N ratio
1	40	0.048	0.25	30	170.76	8	21.35	-26.5859
2	40	0.096	0.5	45	209.21	32	6.54	-16.3086
3	40	0.143	0.75	60	265.52	71.5	3.71	-11.3958
4	40	0.191	1	75	314.98	127.33	2.47	-7.86682
5	40	0.238	1.25	90	331.99	198.33	1.67	-4.47459
6	60	0.048	0.5	60	282.17	24	11.76	-21.406
7	60	0.096	0.75	75	385.36	72	5.35	-14.5707
8	60	0.143	1	90	393.56	143	2.75	-8.7935
9	60	0.191	1.25	30	305.84	238.75	1.28	-2.15102
10	60	0.238	0.25	45	358.26	59.5	6.02	-15.5936
11	95	0.048	0.75	90	464.8	57	8.15	-18.2278
12	95	0.096	1	30	356.17	152	2.34	-7.39627
13	95	0.143	1.25	45	472.24	283.02	1.67	-4.44689
14	95	0.191	0.25	60	513.98	75.60	6.80	-16.648
15	95	0.238	0.5	75	539.33	188.41	2.86	-9.13471
16	145	0.048	1	45	513.97	116	4.43	-12.9296
17	145	0.096	1.25	60	636.09	290	2.19	-6.82241
18	145	0.143	0.25	75	683.43	86.39	7.91	-17.964
19	145	0.191	0.5	90	786.69	230.79	3.41	-10.6517
20	145	0.238	0.75	30	709.96	431.37	1.65	-4.32758
21	225	0.048	1.25	75	910.23	225	4.05	-12.1394
22	225	0.096	0.25	90	985.23	90	10.95	-20.7859
23	225	0.143	0.5	30	867.71	268.12	3.24	-10.2007
24	225	0.191	0.75	45	1100.28	537.18	2.05	-6.22755
25	225	0.238	1	60	1480.95	892.5	1.66	-4.39864

Table 4: ANOVA table for SEC

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cnt.
Model	4	349.318	87.330	13.38	0.000	
Linear	4	349.318	87.330	13.38	0.000	
V	1	16.746	16.746	2.56	0.125	3.6
f	1	138.373	138.373	21.19	0.000	28.8
d	1	193.896	193.896	29.70	0.000	40.4
Φ	1	0.303	0.303	0.05	0.832	0.064
Error	20	130.578	6.529			27.2
Total	24	479.896				100

B. Analysis of Variance for the SEC Model

The experimental results are analyzed with ANOVA to identify the factors that significantly affect the performance measure on the total variance of the results. The ANOVA is carried out at α=0.05 significance level (95%) confidence level) gave results are SEC shown in Table 4. The sources with P-value < 0.05 are considered as highly statistically significant. The coefficient of determination for the developed model R^2 =96.3. Hence, the developed model is statistically significant. From Table 4 it was observed that depth of cut (d) is the most significant parameter followed by feed (f) and Cutting speed (V). The fiber orientation angle (Φ) is insignificant.

C. Trend Analysis of Process Parameters on SEC using

Response Plots

Figures 4a-4c shows response surface plots have been obtained from the RSM model developed for Specific energy consumption (SEC). From figures 4a-4c, it is observed that the specific energy consumption decreases with an increase in cutting speed, feed and depth of cut. As such the specific energy consumption is inversely proportional to the cutting speed, feed and depth of cut.

From the plots, it is also observed that the SEC increases with an increase in fiber orientation angle for all the range of work pieces considered in this investigation. As the fiber orientation angle increases, the fibers are subjected to more compressive stresses hence, while shearing the fibers during machining more amount of power is consumed.

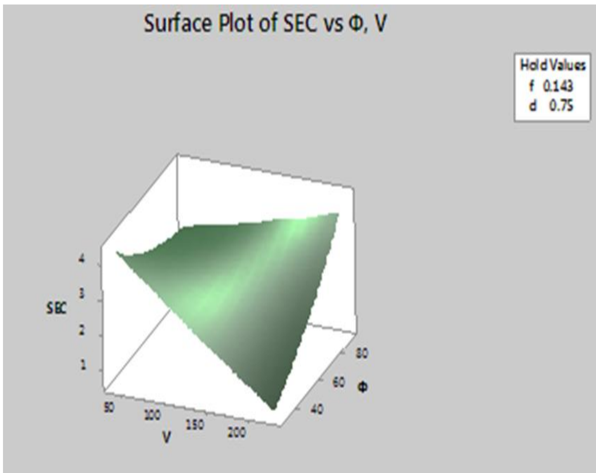

Fig. 4a: Response surface of SEC versus cutting speed and fiber orientation angle

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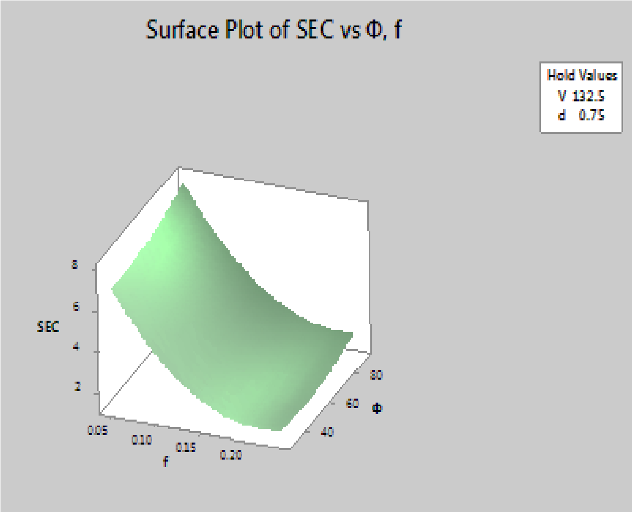

Fig. 4b: Response surface of SEC versus feed rate and fiber orientation angle

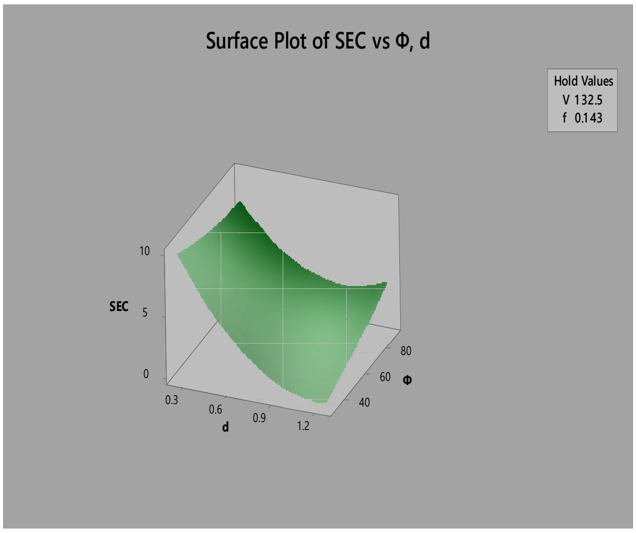

Fig. 4c: Response surface of SEC versus depth of cut and fiber orientation angle

Thus, while machining of GFRP composites high cutting speed, high feed and high depth of cut and low fibre orientation angle should be considered to minimize the specific energy consumption (SEC).

D. S/N Ratio Analysis for Optimum Settings

In Taguchi method the term "Signal" represents the desired value and "noise" represents the undesirable value. The objective of using S/N ratio is the measure of performance to develop products and processes insensitive to noise factors [22]. The process parameters setting with the highest S/N ratio always yield the optimum quality with minimum variance. The MINITAB-18 Software was used to analyze the main effect of S/N ratio on the optimization analysis for SEC. The influence of different control parameters in the machining of GFRP composites can be studied using a response plot. Figure 5 shows the main effect plot and the corresponding S/N response for specific energy consumption (SEC). The overall mean response is represented by the horizontal line at the centre of the curve.

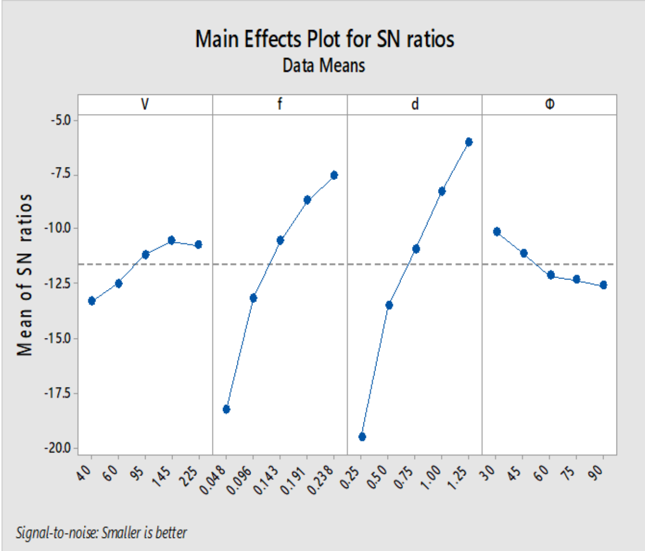

Fig. 5 Main effect plot (SEC) for S/N ratios

From the S/N ratio analysis in Figure 5, the level of the factors with the highest S/N ratio was taken as the optimum level for the response, therefore the optimal control parameters taken as cutting speed 145m/min, feed 0.238mm/rev, depth of cut 1.25mm and fibre orientation angle 30° to minimize the specific energy consumption (SEC) in the machining of GFRP composites.The response table for the S/N ratio is shown in Table 5. From the table, it is observed that depth of cut is the most predominant parameter followed by feed and cutting speed. Fibber orientation angle does not have any influence on SEC.

Table 5: Response Table for Signal to Noise Ratios

Level	Cutting speed, V	Feed f	Depth of cut d	fibre orientation angle, Φ
1	-13.326	-18.258	-19.515	-10.132
2	-12.503	-13.177	-13.540	-11.101
3	-11.171	-10.560	-10.950	-12.134
4	-10.539	-8.709	-8.277	-12.335
5	-10.750	-7.586	-6.007	-12.587
Delta	2.787	10.672	13.509	2.454
Rank	3	2	1	4

E. Optimum Parameter Setting By PSO

MATLAB is used to generate the PSO code. The input control parameters and their levels are fed to the PSO program. It is possible to determine the conditions at which the machining operation has to be carried out to get the optimum specific cutting energy. Figure 6 shows the SEC versus no. of iterations.

Table 6 shows the performance of the optimum combination of control parameters to minimize the SEC. It has been found that the minimum value of specific energy consumption is 1.09 J/mm^3, which at a cutting speed (V= 148.53 m/min), feed (f=0.22 mm/rev), depth of cut of (d=1.16 mm) and fibre orientation angle (Φ=33°). Hence, it is concluded that an optimal combination of control parameters could be obtained using PSO to minimize the machining responses.

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The application of the PSO approach is very much helpful to set the optimal machining conditions in computer-aided machining process for the production of quality goods with acceptable tolerances.

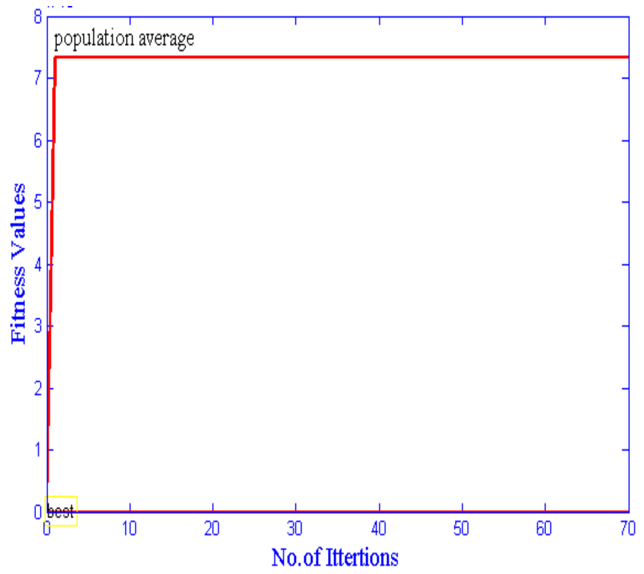

Fig. 6 Performance of PSO

F. Experimental Validation

After the selection of optimal control parameters, confirmation experiments were performed to verify the corresponding SEC under the optimal combination of input parameter. The comparison between the initial experimental condition and optimal conditions are shown in Table 6.

Table 6: Comparison between the initial experimental condition and optimal conditions predicted by PSO

Control Parameters With Units	Initial Conditions	Optimal Conditions Predicted by PSO	Percentage of Variation (%)
Cutting speed (V), m/min	145	148.53	
Feed (f), mm/rev	0.238	0.22	
Depth of cut (d), mm	0.75	1.16	
Fibre Orientation angle (Φ), deg	30	33	
Output responses:			
MRR (mm^3/s)	431.37	631.74	46.44
SEC (J/mm^3)	1.65	1.09	33.93

From the comparison Table 6, it is observed that there is a 46.44% improvement in MRR and 33.93% reduction in SEC.

The validity of the optimized procedure has been checked through confirmation experiments. The confirmation experiment has been performed on a GFRP composite tube of 30° fibre orientation angle. Table 7 shows the percentage of error between the predicted and experimental validation values. From this analysis, it is observed that the calculated error is very small which confirms the excellent reproducibility of the experimental conditions.

Table7. Experimental validation with optimal parameter settings

	V (m/min)	f (mm/rev)	d (mm)	Φ (deg)	MRR (mm^3/s)	SEC (J/mm^3)
Parameters Predicted by PSO	148.53	0.22	1.16	33	631.7	1.09
Experimental conditions	148.53	0.22	1.16	30	668.8	1.025
% Error					5.87	5.96

IV. CONCLUSIONS

In this investigation, Particle Swarm Optimization (PSO) was successfully implemented to optimize the specific energy consumption in Turing of GFRP composites with PCD cutting tool insert. A quadratic model was developed for specific energy consumption using response surface methodology. From the analysis of the response plots, it is observed that the specific energy consumption decreases with an increase in cutting speed, feed and depth of cut. From the plots, it is also observed that the SEC increases with an increase in fiber orientation angle for all the range of work-pieces considered in this investigation. The minimum specific energy consumption (SEC) was observed at an optimal combination of control parameters like cutting speed (V=148.53), feed (f=0.22mm/rev), depth of cut (d=1.16mm) and fiber orientation angle (33°). As compared with the initial experimental condition, an optimal combination of control parameters the MRR has increased by 46.44%, whereas there is a reduction of SEC by 33.93%. The Confirmatory experimental results also validated the efficiency of the PSO algorithm.

LIMITATIONS AND FUTURE WORK

The limitations of Particle swarm optimization are that it easily falls into the local optimum in high dimensional space and has a low convergence rate in the iterative process.

- The number of control parameters can be extended and hence, the database can be improved by extensive experimentation.
- The experiments can be replicated with other cutting tool inserts.
- The experimental work can be extended to the other machining process.

In the present work, the experimental data has been modelled and analyzed by Response surface methodology (RSM). The same problem can be modelled by an Adaptive Neuro-Fuzzy Inference System (ANFIS).

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Conflict of Interest

Authors declare that no conflict of interest

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