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Multiple Performance Characteristic Optimization in Turning of GFRP Composites Using Fuzzy Logic

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Abstract: Glass fiber reinforced plastic (GFRP) composite materials are continuously replacing the traditional engineering materials and are finding increased applications in many fields, such as automobile, marine, sport goods etc,. Machining of these materials is needed to achieve near-net shape. In machining of composite materials, optimization of process parameters is an important concern. This paper presents, the use of Fuzzy logic combined with Taguchi method for the optimization of multiple performance characteristics considering surface roughness, cutting force, specific cutting pressure and cutting power. Experiments were planned using Taguchi's L_{25} orthogonal array with the cutting conditions prefixed. The process parameters considered are work piece (fiber orientation), cutting speed, feed and depth of cut. The machining tests were performed on a lathe using carbide (K20) cutting tool. The results indicated that the optimization technique is greatly helpful in optimizing the multiple performance characteristics simultaneously in machining of GFRP composites.

Key words: GFRP composites, Taguchi, Fuzzy logic, Optimization, Carbide (K20).

I. Introduction

Glass fiber reinforced plastics (GFRP) composites are widely used in different engineering industries because of their excellent properties such as high strength to weight ratio, high fracture toughness, and excellent corrosion and thermal resistance. They are finding applications in automobile, aeronautical and marine industries. However the users of FRP composites are facing difficulties to machine it, because of delamination, fiber pull out, short tool life, matrix debonding, burning and formation of powder like chips. To minimize the damage in machining, it is important to monitor process variables such as cutting speed, feed, depth of cut etc,. In most applications, traditional metal cutting machine tools and techniques are still being used. But machining of FRP composites is different from that of conventional materials because of its inhomogeneity [1]. Bhatnagar et al [2], studied how the fiber orientation influence both the quality of the machined surfaces and tool wear. The machinability of composite materials is influenced by the type of fiber embedded in the composites and more particularly by the mechanical properties. On the other hand, the selection of cutting parameters and the cutting tools are dependent on the type of fiber used in the composites and which is very important in the machining process. Santhana krishnan [3] studied the mechanism of material removal during GFRP machining and the type of wear in high-speed steel tools with the help of scanning electron microscope. Ramulu et al. [4], carried out a study on machining of polymer composites and concluded that higher cutting speeds give better surface finish. Tekeyama et al, [5] studied the surface roughness on machining of GFRP composites, according to them, higher cutting speed produce more damage on the machined surface. This is attributed to higher cutting temperature, which results in local softening of work material. They also studied the machinability of FRP composites using the ultra sonic machining technique. Davim and Mata [6] studied the influence of cutting parameters on surface roughness in turning glass-fiber reinforced plastics using statistical analysis. The machinability of GFRP composites indicates the relative ease with which a given material can be machined using appropriate tool and machining parameters. Cutting force, cutting power and specific cutting pressure are some of the criteria to evaluate machinability.

Koplev et al. [7], have investigated the process of machining carbon fiber reinforced plastics (CFRP). They measured cutting forces in both parallel and perpendicular to the fiber orientation using quick stop experiments. Sang-ook et al. [8] have experimentally investigated the machinability of GFRP by means of different tool materials and geometries and concluded that by proper selection of cutting tool material and geometry, excellent machining of the work piece can be achieved. Wang et al. [9] have studied, both analytically and experimentally, the orthogonal cutting mechanism of unidirectional graphite/epoxy composites with a diamond tool. They have developed a regression model to predict cutting force in terms of rake angle, clearance angle, depth of cut and cutting speed. Apart from fiber orientation, tool geometry has consistently been noted as a critical cutting parameter which influences the cutting force, surface quality and tool wear [10]. Davim and Mata [11] presented an optimization study of surface roughness in turning FRPs tubes manufacturing by filament winding and hand lay-up, using polycrystalline diamond cutting tools. Optimal cutting parameters were identified to obtain a certain surface roughness (*Ra* and *Rt/R*max), corresponding to international dimensional precision (ISO) IT7 and IT8 in the FRP work pieces, using multiple analysis regression (MRA). Additionally, the optimal material removal rates were identified. Palanikumar et al. [12] discussed the application of the Taguchi method with fuzzy logic to optimize the machining parameters for machining of GFRP composites with multiple characteristics. A multiple performance characteristic index (MPCI) was used for optimization. The machining parameters viz., work piece (fiber orientation), cutting speed, feed rate, depth of cut and machining time were optimized with consideration of multiple performance characteristics viz., metal removal rate, tool wear, and surface roughness. The results from confirmation runs indicated that the determined optimal combination of machining parameters improved the performance of the machining process. Rajesh Kumar varma et al [13] have performed optimization study made on machining of randomly oriented glass fiber reinforced (GFRP) polymer composite rods with different process environment. An expert system based on fuzzy rule based modeling approach combined with Taguchi's robust design philosophy has been adopted to evaluate the optimal process parameters thereby satisfying conflicting requirements of material removal rate (MRR) and surface roughness of the machined composite product. Effectiveness of the proposed model has been illustrated in this reporting. In this study, a fuzzy reasoning of the multiple performance characteristics has been developed based on fuzzy logic. As a result, optimization of complicated multiple performance characteristics can be transformed into the optimization of a single multi-performance characteristics index (MPCI). In this paper an attempt is made to optimize the process parameters in turning GFRP composites with multiple performance characteristics has been investigated viz., Surface roughness (R_a) cutting force (F_z), specific cutting pressure (K_s)and cutting power (P).

II. Material and Methodology

The work material used for the present investigation is glass fiber reinforced plastics (GFRP) of different fiber orientation angles, whose angle vary from 30^o~90^o in steps of 15^o. The inner diameter of the tube is 30mm and outer diameter 60mm and length 500mm respectively. The tubes used in this investigation are manufactured using filament winding technique. The fiber used in the tube is E-glass and the resin used is epoxy. The fiber orientation angle on the tubes has been set during the manufacture of tubes. The experiments are planned using Taguchi's L_{25} orthogonal array (Davim and Mata 2005) in the design of experiments (DoE), which helps in reducing the number of experiments. The cutting parameters considered in this investigation is cutting speed (V), feed (f), Depth of cut (d) and work piece (fiber orientation 'Φ') in degrees. Since all the considered cutting parameters are multi-level variables and their outcome effects are not linearly related. The studies related to the GFRP composites indicated that the higher cutting conditions leads to high tool wear and poor surface finish (Palanikumar *et al.* 2006). The turning parameter used and their levels chosen are given in Table 1. All the GFRP tubes are turned on a BHARAT all-geared lathe of model NAGMATI-175 with a maximum speed of 1200 rpm and power of 2.25KW. The ISO specification of the tool holder used for the turning operation is a WIDAX tool holder PC LNR 2020 K12 and the tool insert is carbide (K20) of type CNMA 120408. During machining, the cutting force developed was measured using a KISTLER quartz 3-component dynamometer type 9257B. The dynamometer measures the active cutting force regardless of its application point. The dynamometer is connected to a 3-channel charge amplifier type 5807A through a connecting cable type 1687B5, this in turn is connected to the PC by a 37-pin cable from the A/D board. The dynamometer is calibrated for the cutting force in the range from 0 to 1000N. To get accuracy in measuring the cutting force, it is measured three times and average of cutting forces has been taken for analysis. The average surface roughness was measured for three types and average values are taken for the analysis. The schematic layout of the experimental setup is shown in Figure 1.

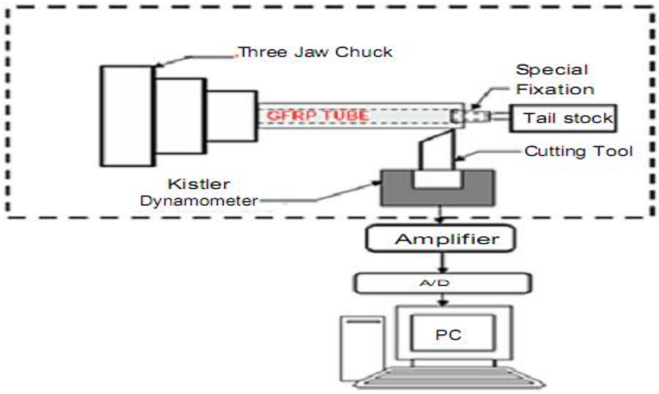

Figure1.Schematic layout of the Experimental setup

Table 1. Process parameters and their levels

Process parameters With units	Notation	Variable	Levels 1	2	3	4	5
Speed, m/min	V	x_1	40	60	95	145	225
Feed, mm/rev	f	x_2	0.048	0.096	0.143	0.191	0.238
Depth of cut, mm	d	x_3	0.25	0.5	0.75	1.0	1.25
Fiber orientation angle, deg	Φ	x_4	30	45	60	75	90

The specific cutting pressure was chosen as a process indicator to determine the machinability of GFRP composites. It is usually influenced by the cutting speed and material. For all the experimental runs, the specific cutting pressure (K_s) was estimated from the measured cutting force value using the equation 1.

$$Ks = \frac{Fz}{f * d} \text{ N/mm}^2 \quad (1)$$

Cutting power is the product of main cutting force and the cutting velocity and is a better criterion for design and selection of any machine tools. Power consumption may be used for monitoring the tool conditions. The sharpness of the tool tip influences forces and power consumption because, the tool rubs against the machined surface and makes the deformation zone ahead of the tool. Worn out tools require higher forces and higher cutting power. The cutting power is estimated by using the expression shown in equation 2.

$$\text{Cutting Power (P)} = F_z * V \quad \text{Watts} \tag{2}$$

Optimization of Multiple Performance Characteristics With Fuzzy Logic

Experimental design methods were developed originally by Fisher. However, classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out as the number of the process parameters involved. To solve this, the Taguchi method uses a special design of orthogonal array to study the entire parameter space with only a small number of experiments. The experimental results are then transformed into a signal-to-noise (S/N) ratio. The S/N ratio can be used to measure the deviation of the performance characteristics from the desired values. Usually, there are three categories of performance characteristics in the analysis of the S/N ratio the lower-the-better, the higher-the-better, and the nominal-the-better [16]. Regardless of the category of the performance characteristic, a larger S/N ratio corresponds to better performance characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to identify the process parameters that are statistically significant. The optimal combination of the process parameters can then be predicted based on the above analysis. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design. In this paper, the use of fuzzy logic to deal with the optimization of a process with multiple performance characteristics is reported. First, several fuzzy rules are derived based on the performance requirement of the process. The loss function corresponding to each performance characteristic is fuzzified and then a single MPCI is obtained through fuzzy reasoning on the fuzzy rules. The MPCI can be used to optimize the process based on the Taguchi approach. In this investigation experimental data has been converted in to corresponding S/N ratio using equation 3-4. For surface roughness Ra, a Lower-the Better (LB) criterion and for the cutting force, a Lower the-Better (LB) criterion, for specific cutting pressure, a Lower the-Better (LB) criterion and for cutting power, a Lower the-Better (LB) criterion, has been selected.

The SN ratio with Lower-the-Better (LB) characteristics can be expressed as:

$$\eta_{ij} = -10 \log\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}^2\right) \tag{3}$$

The SN ratio with Higher-the-Better (HB) characteristics can be expressed as:

$$\eta_{ij} = -10 \log\left(\frac{1}{n}\sum_{j=1}^{n} \frac{1}{y_{ij}^2}\right) \tag{4}$$

The SN ratios have been normalized based on the Higher-the Better (HB) criterion, the normalization can be expressed as:

$$x_i = \frac{yi\ (k) - \min yi\ (k)}{\max yi(K) - \min yi\ (k)} \tag{5}$$

The S/N ratio for the machining responses, their normalized values and MPCI values are shown in Table 2.

Table 2. S/N ratio for the machining responses, their normalized values and MPCI values

Exp. No`	S/N Ratio				Normalized				MPCI
	Surface roughness (R_a)	Cutting Force (F_z)	Specific cutting pressure (K_s)	Cutting power (P)	Ra	Fz	Ks	P	
1	-9.7405	-48.169	-29.469	-47.530	0.56343	0.7814	0	1	0.25
2	-10.7926	-49.933	-18.956	-49.059	0.38840	0.5427	0.4266	0.9066	0.5
3	-11.8551	-52.003	-12.821	-49.907	0.21164	0.2626	0.6755	0.8548	0.41
4	-12.5741	-53.487	-9.1818	-51.282	0.09203	0.0618	0.8232	0.7709	0.5
5	-13.1273	-53.944	-6.4568	-52.404	0	0	0.9338	0.7023	0.5
6	-10.6569	-49.010	-23.903	-51.507	0.41098	0.6676	0.2258	0.7571	0.488
7	-11.1077	-51.717	-16.025	-53.173	0.33598	0.3013	0.5455	0.6554	0.312
8	-11.7632	-51.900	-10.428	-53.534	0.22693	0.2766	0.7726	0.6333	0.538
9	-11.4363	-49.709	-5.3434	-52.904	0.28131	0.5730	0.9790	0.6718	0.75
10	-12.1476	-51.084	-17.424	-52.915	0.16298	0.3870	0.4887	0.6712	0.25
11	-9.5117	-49.353	-21.300	-56.418	0.60149	0.6211	0.3314	0.4573	0.5
12	-8.1011	-47.041	-11.111	-54.748	0.83616	0.9340	0.7449	0.5592	0.75
13	-10.7185	-49.491	-7.535	-56.572	0.40073	0.6025	0.8900	0.4479	0.25
14	-11.9267	-50.227	-18.705	-56.276	0.19973	0.5029	0.4368	0.4659	0.25
15	-12.2627	-50.645	-11.586	-57.090	0.14383	0.4463	0.7256	0.4162	0.25
16	-7.1163	-46.554	-16.548	-57.835	1	1	0.5244	0.3707	0.75
17	-9.0413	-48.405	-9.496	-58.745	0.67975	0.7495	0.8105	0.3152	0.5
18	-10.8156	-49.029	-21.036	-59.766	0.38457	0.6650	0.3421	0.2528	0.25
19	-11.0645	-50.251	-13.793	-61.058	0.34317	0.4996	0.6361	0.1739	0.5
20	-9.7048	-49.360	-7.557	-60.256	0.56937	0.6203	0.8891	0.2229	0.448
21	-8.4321	-47.702	-14.942	-61.986	0.78110	0.8446	0.5895	0.1173	0.561
22	-11.0881	-48.390	-24.822	-63.907	0.33924	0.7515	0.1885	0	0.25
23	-9.9577	-47.286	-14.008	-62.575	0.5273	0.9008	0.6273	0.0813	0.5
24	-10.3336	-49.349	-7.8469	-62.451	0.46476	0.6217	0.8774	0.0888	0.392
25	-10.4515	-51.965	-4.8259	-63.842	0.44515	0.2678	1.0000	0.0039	0.5

Fuzzy Logic System

Fuzzy logic has rapidly become one of the most successful of today's technologies for developing sophisticated control systems. Fuzzy logic (FL) has been used in many practical engineering situations because of its capability in dealing with imprecise and inexact information. The powerful aspect of fuzzy logic is that, it mimics the human decision making with an ability to generate precise solutions from certain or approximate information. The combination of incomplete, imprecise

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22nd March 2014

information and the imprecise nature of the decision-making process make fuzzy logic very effective in modeling complex engineering, business, finance and management systems which are otherwise difficult to model. Fuzzy systems make its decisions on inputs and outputs in the form of linguistic variables. The variables are tested with IF-THEN rules, which produce one or more responses depending on which rules they are asserted. The response of each rule is weighed according to the degree of membership of its inputs and the centroid of the responses is calculated to generate the appropriate output [17&18]. Figure 2 shows the fuzzy inference system, it is also known as fuzzy rule based system. Fuzzy logic system comprises of a fuzzifier, membership function, a fuzzy rule base, an inference engine and defuzzifier. The fuzzifier uses membership function to fuzzyfy S/N ratios of each performance characteristic. Next the inference engine (Mamdani fuzzy inference sytem) performs fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally, the defuzzifier converts fuzzy predicted value into a Multi Performance Characteristic Index (MPCI) response can be used to find the better accuracy of output of the MPCI in turning of GFRP composites with CBN tool. In calculating MPCI in FIS system, various membership functions (MFs) have been assigned to the input variables i.e., normalized S/N ration of surface roughness (R_a), normalized S/N ration of cutting force (F_z), normalized S/N ration of specific cutting pressure (K_s), and normalized S/N ration of cutting power (P). The membership functions selected for input variables are "Low", "Low Medium", "Medium", "High Medium", and "High" as shown in Figure 3-6. Five membership functions have been selected for MPCI: "Very small" "Small", "Medium", "Large", and "Very Large" as shown in Figure 7.

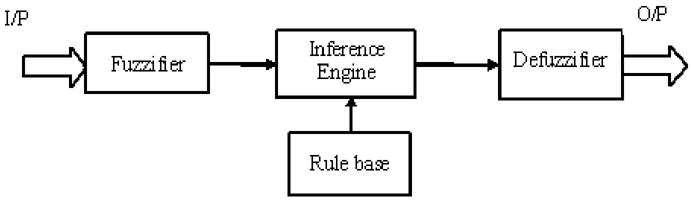

Figure1: Fuzzy Inference system

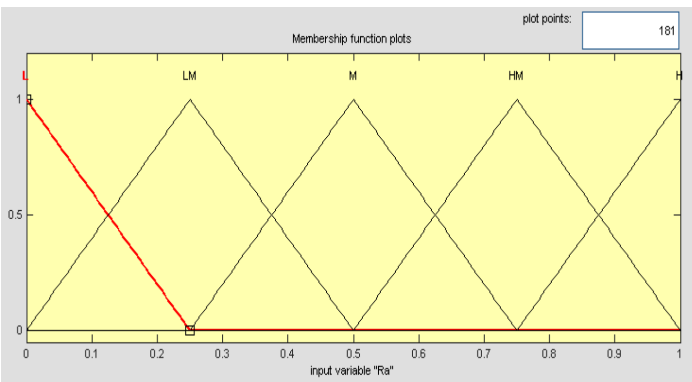

Figure 3: Membership functions for R_a (Normalized S/N ratio for R_a)

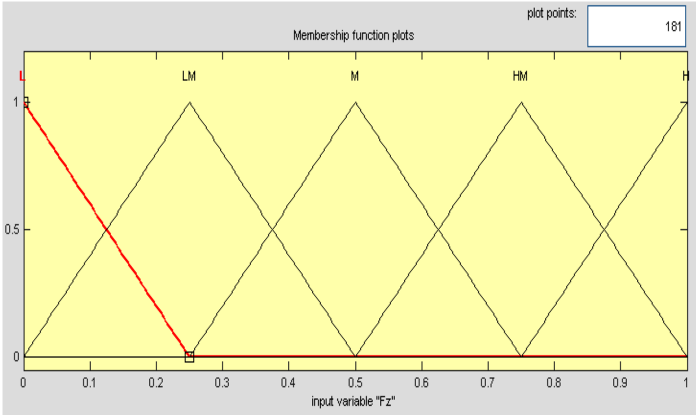

Figure 4: Membership functions for F_z (Normalized S/N for F_z)

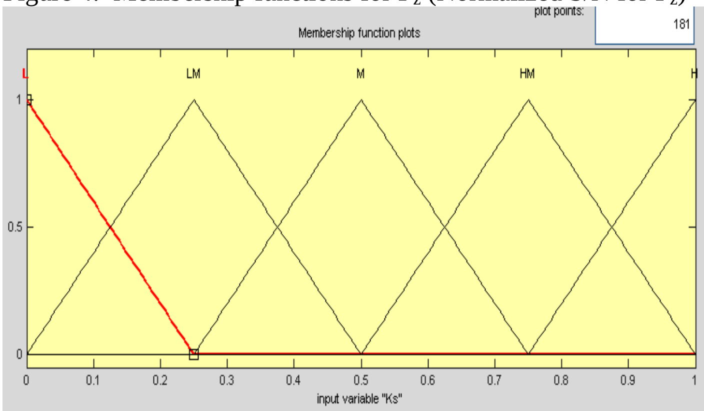

Figure 5: Membership functions for K_s (Normalized S/N ratio for K_s)

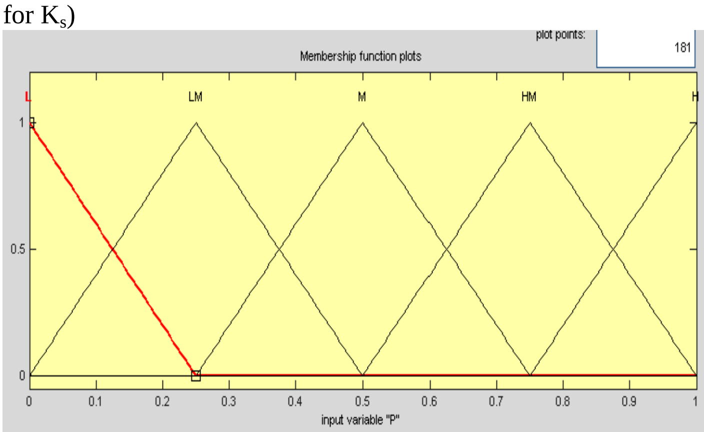

Figure 6: Membership functions for P(Normalized S/N ratio for P)

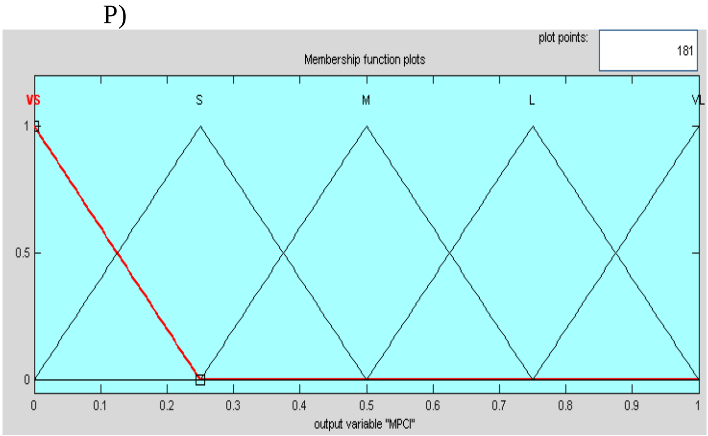

Figure 7: Membership functions for MPCI

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III. Results and Discussions

Glass fiber reinforced plastics (GFRP) composite materials are a feasible alternative to engineering materials. They have excellent properties and are being extensively used in variety of engineering applications. However, the users of FRP are facing difficulties to machine it, because of its anisotropic properties. When GFRP composites are machined, discontinuous chips in powder form are produced, which is entirely different from machining of metals. The machining of GFRP composites differ from machining of metals, due to this fact optimization of multiple performances is difficult in machining of GFRP Composites. In this investigation fuzzy logic combined with Taguchi method was employed for the optimization of multiple performance characteristics viz., Surface roughness (R_a) and Cutting force (F_z), specific cutting pressure (K_s) and cutting power (P) in turning of GFRP composites with carbide (K20) tool insert.

MPCI Optimal Process Parameters for Turning of GFRP Composites

The normalized S/N ratio for surface roughness (R_a), cutting force (F_z) specific cutting pressure (K_s) and cutting power (P) are taken as input variables. Table 2 shows the MPCI values acquired from the fuzzy logic system constructed in the previous section. Figure 8 shows the effect plot for MPCI, larger is the MPCI smaller is the variance of the performance characteristic around the desired value. However, the relative importances amongst the machining parameters for the multiple characteristics still need to be known so that the optimal combination of the machining parameters can be determined more accurately. Based on the results shown in Figure 8, the optimal combination of process parameters in turning of GFRP composite is determined. The following parameter settings have been identified to yield the best results: Cutting speed (V)= 145m/min, feed (f) = 0.048mm/rev, Depth of cut (d)= 1.0mm and fiber orientation angle (Φ)= 30^o.

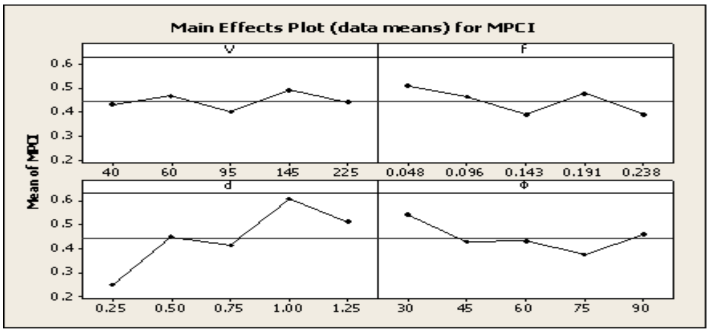

Figure 8: Main effect plots for MPCI

Table. 3 Response table for MPCI

Levels	V	f	d	Φ
1	0.4320	**0.5098**	0.2500	**0.5396**
2	0.4676	0.4624	0.4476	0.4284
3	0.4000	0.3896	0.4124	0.4296
4	**0.4896**	0.4784	**0.6076**	0.3746
5	0.4406	0.3896	0.5122	0.4576
Rank	4	3	1	2

Analysis of Variance

The purpose of the ANOVA is to investigate which process parameter significantly affects the performance characteristics. This is accomplished by separating the total variability of the multi-performance characteristic index (MPCI), which is measured by the sum of the squared deviation from the total mean of the MPCI, into contribution by each of the process parameter and the error. The p-value provides a way of testing the relationship between the independent variable and the response. With a pre-selected α-level, and a p-value smaller than α indicates that the coefficient is significantly different from zero at the α-level. A commonly used cut-off value for the p-value is 0.05. In addition, the F-test determines which process parameter has a significant effect on the performance characteristic. Usually, the change of the process parameter has a significant effect on the performance characteristic when the F value is large. The table 4 shows the analysis of variance for MPCI, from that table it is inferred that the depth of cut, a fiber orientation angle (Φ) and feed rate are the significant parameters affecting the multiple performance characteristics.

Table 4. Analysis of Variance for MPCI

Factor	df	**SS**	MS	F	% Contr
V	4	0.02354	0.00589	0.43	3.82
f	4	0.05876	0.01469	1.07	9.55
d	4	0.35022	0.08756	6.38	56.93
Φ	4	0.07286	0.01822	1.33	11.84
Error	8	0.10973	0.01372		17.83
Total	24	0.61511			

IV. Conclusions

The present study deals with the investigation on some aspects of machinability characteristics viz., surface roughness, cutting force, specific cutting pressure and cutting power in turning of GFRP composite materials for the range of fiber orientation angle (30^o~90^o) with Carbide(K20) cutting tool insert. Based on the experimental results the following conclusions are drawn.

1. The optimal combination of process parameters for the MPCI are: cutting speed (V)=145m/min, feed (f)= 0.048mm/rev, Depth of cut (d)=1.0mm, Fiber orientation angle(Φ)= 30^o.
2. Based on ANOVA results, the process parameters most significantly influencing the MPCI are depth of cut (d), fiber orientation angle (Φ), feed rate (f).
3. Combining the Taguchi method and fuzzy logic facilitates simultaneous acquisition of low surface roughness (R_a) low cutting force (F_z), low specific cutting pressure (Ks) and low cutting power in machining GFRP Composites with carbide (K20).

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