9-2022

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Available online at www.sciencedirect.com

Manufacturing Letters

Manufacturing Letters 33 (2022) 29–40

50th SME North American Manufacturing Research Conference (NAMRC 50, 2022)

Turning of Carbon Fiber Reinforced Polymer (CFRP) Composites: Process Modeling and Optimization using Taguchi Analysis and Multi-Objective Genetic Algorithm

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Abstract

Carbon Fiber Reinforced Polymer (CFRP) composites have been widely used in aerospace, automotive, nuclear, and biomedical industries due to their high strength-to-weight ratio, corrosion resistance, durability, and excellent thermo-mechanical properties in non-oxidative atmospheres. Machining of CFRP composites has always been a challenge for manufacturers. In this research, a comparative study was performed between the optimal machining parameters of coated and uncoated carbide inserts obtained from the Multi-Objective Genetic Algorithm during turning of CFRP composites. It was found that coated carbide inserts provide lower tool wear and surface roughness, but higher cutting forces compared to those of uncoated carbide inserts during turning of CFRP composites. Taguchi Analysis was performed to investigate the effects of machining parameters (cutting speed, feed rate and depth of cut) on the output characteristics including cutting force, surface roughness and tool wear. The feed rate was found as the most significant machining parameter in turning of CFRP composites to minimize cutting force and surface roughness using both coated and uncoated carbide inserts. However, feed rate and cutting speed has been found as the most significant machining parameters for coated and uncoated carbide inserts respectively to minimize the tool wear. Regression Analysis has been performed to develop mathematical models for cutting force, surface roughness and tool wear as a function of cutting speed, feed rate and depth of cut. Higher R^2 values and well fitted regression lines of normal probability plots in regression analysis indicate that the coefficients of mathematical models are statistically significant. The significance of this study is to emphasize the differences of performances between coated and uncoated carbide inserts during turning of CFRP composites in terms of cutting force, tool wear and surface roughness with the combination of different machining parameters (cutting speed, feed rate and tool wear) using data analysis tools such as Taguchi Analysis, Regression Analysis and Multi-Objective Optimization.

Keywords: CFRP composites; Taguchi Analysis; Multi-Objective Genetic Algorithm

1. Introduction

Traditional machining of CFRP arises some problems including high cutting forces, high torque, high surface roughness, severe delamination, high tool wear, high cutting temperature, etc. [1,2]. Turning of CFRP composites involves with a lot of challenges such as fiber delamination, rapid tool wear, high cutting force and surface roughness etc. Due to extensive abrasiveness, tool wear is very high during turning of CFRP composites. All the response characteristics such as cutting force, tool wear and surface roughness depend largely on the variation of cutting parameters during turning process. Finding the best combination of machining parameters such as cutting speed, feed rate and depth of cut is a major concern while turning the CFRP composites. So, optimization of cutting parameters is very important to improve the quality of the machined parts, reduce the machining cost and to increase the effectiveness of machining process [3].

In this paper, an extensive investigation has been performed on the turning of CFRP composites using coated

and uncoated carbide inserts with the variation of different cutting parameters and the corresponding output characteristics have been studied using statistical analysis tools. Taguchi Analysis has been used to investigate the effects of machining parameters on response characteristics and Linear Regression Analysis has been used to develop the mathematical models for response characteristics. Multi-Objective Genetic Algorithm has been applied to find the optimal machining parameters to minimize the cutting force, surface roughness and tool wear. Finally, a comparative study has been performed based on the optimal machining conditions of coated and uncoated carbide inserts obtained from multi-objective optimization.

Nomenclature	
v	Cutting speed
f	Feed rate
DoC	Depth of cut
Fc	Cutting force
Ra	Surface roughness
T	Tool wear

1.1 Modeling

Researchers have focused on the prediction of the cutting force, tool wear, tool tip temperature and surface roughness during turning of CFRP composites using different modeling technique such as Finite Element Modeling (FEM), fuzzy modeling etc. Rajasekaran et al. [4] modelled and predicted the machining force and specific cutting pressure using fuzzy logic during turning of CFRP composites. In another study, Rajasekaran et al [5] developed a fuzzy model to predict the cutting force during turning of CFRP using PCD cutting tool. Belmonte et al. [6] performed turning of CFRP composites using uncoated and CVD diamond coated Si_3N_4 cutting tools and reported that CVD coated Si_3N_4 cutting tools show better performance compared to the uncoated Si_3N_4 cutting tools during turning of CFRP in terms of lower cutting force and lower tool wear. Chang et. al. [7] developed a finite element model for tool tip's surface temperature during oblique cutting of CFRP in turning process. In another experiment, Chang [8] used nine types of chamfered main cutting-edge nose radius tools during turning of CFRP composites and developed a cutting temperature model to study the cutting temperature of tip's surface with the variations of shear and friction plane areas occurring in tool nose situations.

1.2 Performance study of CFRP turning process

Several researchers have studied the performance of different tool materials and tool geometry during turning of CFRP composites. Ferreira et al. [9] studied the performance of ceramics, cemented carbide, cubic boron nitride (CBN), and Poly-crystalline diamond (PCD) tools during turning of CFRP composites and found that PCD cutting tools are best suited to the finish turning of CFRP composites. They concluded that the fiber orientation, matrix content and fiber type have significant impacts on the machinability of CFRP composites. Rahman et. al. [10] studied the machinability of CFRP using different cutting tool inserts such as uncoated tungsten carbides, ceramic, and cubic boron nitride (CBN) varying machining parameters and made comparison among the cutting inserts based on the chip formation, tool wear, surface roughness and relative performance of different inserts.

Rajasekaran et al. [11,12] studied the influence of cutting parameters on surface roughness during turning of CFRP composites using ceramic cutting tool and reported that the most influencing cutting parameters on surface roughness is the feed rate because surface roughness increases with the increase of feed rate, however the surface roughness tends to get improved with the increase of cutting speed. They also studied the influence of cutting parameters on surface roughness during turning of CFRP composites using CBN cutting tool and reported that surface roughness increases with the increase of feed rate but decreases with the increase of cutting speed. So, a combination of lower feed rate and higher cutting speed can result in an improved surface finish. However, depth of cut was found insignificant for surface finish during turning of CFRP composites. Sauer et. al. [13] performed turning of CFRP and identified a strong relation between cutting force and the cross-section of undeformed chip. Demir et. al. [14] studied the effects of tool approaching angle, feed rate and spindle speed on the shape of the chip, length of fibers, surface roughness, and tool wear during turning of CFRP composites and reported that feed rate is the most influencing factor during turning of CFRP followed by tool approach angle and spindle speed.

1.3 Optimization

Several researchers have studied the process optimization during turning of CFRP using different objective functions and optimization techniques [3, 15-18]. Various algorithm and techniques have been used for optimization such as Harmony Search (HS) algorithm [19], JAYA algorithm [20], Teaching Learning Based Optimization (TLBO) algorithm [21,22], Imperialist Competitive Algorithm (ICA) [23], Genetic Algorithm (GA) [17], fuzzy logic, scatter search technique, Taguchi technique and Response Surface Methodology.

Abhishek et al. [24] applied Harmony Search (HS) algorithm to optimize cutting force and surface roughness during turning of CFRP composites using HSS cutting tool and compared the results with those of Genetic Algorithm (GA). Kumar et. al. [25] applied Taguchi's design of experiment, artificial neural network, and genetic algorithm to predict the cutting force and optimize the machining parameters during turning of CFRP composites using a carbide cutting tool. Abhishek et. al [23] applied JAYA algorithm to optimize machining parameters during turning of CFRP composites and compared the results with TLBO, GA, and ICA. They found a good consistency among the results obtained from different algorithms. Abhishek et al. [26] analysed turning of CFRP using ICA and compared the results with that of GA. They [27] also used HS and TLBO algorithm in another study. Ganesan et al. [28] used GA to perform

multi-objective optimization during turning of CFRP composites.

2. Methodology

2.1 Taguchi Design of Experiment

Taguchi L_9 orthogonal array has been used to design the experiments because Taguchi Design of Experiment reduces the number of experiments, improves the quality of performance, and provides robust design by reducing the variation. Tables 1 and 2 illustrate the level of factors and Taguchi Design of Experiments respectively.

Table 1: Input factors and corresponding levels

Factors	Level 1	Level 2	Level 3
Cutting speed (m/min)	75	100	125
Feed rate (mm/rev)	0.05	0.075	0.1
Depth of cut (mm)	0.1	0.15	0.2

Table 2: DOE using Taguchi L_9 orthogonal array

Experiment	Level of factors		
	Cutting Speed	Feed rate	Depth of cut
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

2.2 Taguchi Analysis

In Taguchi analysis, response characteristics are classified into two categories- Signal and Noise. Signal is defined as the desirable effects and the Noise is defined as the undesirable effects of the response characteristics. Taguchi analysis uses the Signal to Noise (S/N) ratio to identify the optimal control parameter setting which minimizes the effects of noise factors. The higher the value of S/N ratio, the lower the effect of noise factors on the response characteristics.

2.3 Regression Analysis

Regression analysis is used as a statistical tool to determine the relationship between the output characteristics and input parameters. Simple Linear Regression is the most popular type of regression analysis method. The goodness of fit for a linear regression model is determined using a goodness of fit measure value called R^2 which refers to the statistical measurement of how close the data values are to the fitted regression line. R^2 value can be represented as the following equation-

$$R^2 = \frac{\text{Explained variation}}{\text{Total variation}} \quad (1)$$

Here "Explained variation" refers to the variation of the data set used in the linear regression modelling and "Total variation" refers to the total variation of the observed data points. The value of R^2 ranges between 0-100%. A higher value of R^2 indicates that there is a strong relationship between the machining parameters and the response characteristics.

2.4 Genetic Algorithm (GA)

Genetic Algorithm (GA) has been used in this study to perform the multi-objective optimization. The significance of using GA in this study is that it does not require any complex mathematical operations and can work with all types of objective functions and constraints which are among the major benefits of using GA over other optimization algorithms. In Multi-Objective Genetic Algorithm, all the non-dominated solutions are separated from the remaining pareto solutions, and these non-dominated solutions are called Pareto optimal solution. A pareto front is plotted using these pareto optimal solutions and the desired optimal solution is selected from this plot based on the preference and judgement of decision maker.

3. Experiment

3.1 Cutting tool and workpiece material

In this study DNMG442-QM 2220 carbide cutting tools with ($TiCN/AI_2O_3/TiN$) coating and DNMG442QM H13A uncoated carbide cutting tools were used to perform turning of CFRP composites in CNC lathe machine. $TiCN/AI_2O_3/TiN$ coating was used due to the low cost and the significant wear resistant properties as reported in the literature. The cutting tools were diamond shaped with 0.8 mm corner radius and 55° included angle. Round bars of 40 mm diameter of CFRP composites (fiber orientation 0°) have been used as workpiece. Experiments were performed without any coolant.

3.2 Cutting force, tool wear and surface roughness measurement

Cutting force was measured using Kistler 9255C Dynamometer. Tool wear was measured using Keyence VHX-5000 optical microscope. Surface roughness was measured using MahrSurf M300C profilometer. Figure 1 shows the cutting force, tool wear and surface roughness measurement set up.

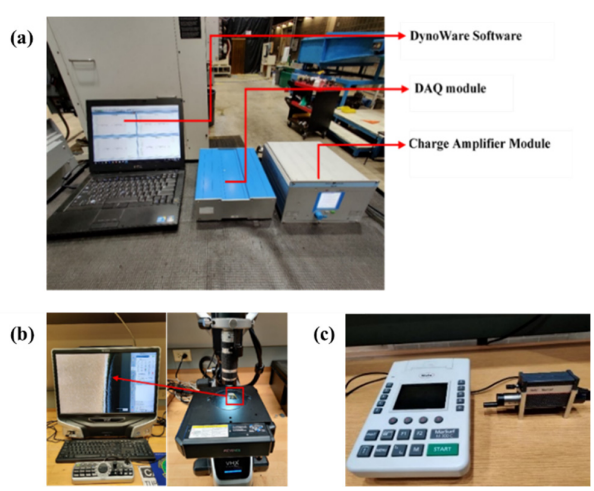

Fig 1. (a) cutting force measurement set up; (b) tool wear measurement set up ;(c) surface roughness measurement set up

3.3 Experimental setup

Ganesh KSL-5210T CNC turning machine was used to perform the turning operation in this study. Machine set up mainly consists of workpiece, cutting tool and dynamometer set up. Figure 2 illustrates a schematic diagram of experimental set up and tool path, cutting force direction.

4. Results & Discussion

Table 3 & 4 provide the data obtained from the turning of CFRP composites using coated and uncoated carbide inserts respectively. Experiments were performed based on Taguchi L_9 orthogonal array.

Table 3. Taguchi L_9 orthogonal array and the observed response values using coated carbides

Cutting Speed (m/min)	Feed rate (mm/rev)	DOC (mm)	Cutting Force (N)	Surface Roughness (µm)	Tool Wear (mm)
75	0.05	0.1	28.38	1.14	0.33
75	0.075	0.15	34.65	1.18	0.36
75	0.1	0.2	44.73	1.21	0.40
100	0.05	0.15	27.34	1.11	0.34
100	0.075	0.2	35.42	1.17	0.38
100	0.1	0.1	43.15	1.22	0.41
125	0.05	0.2	26.31	1.12	0.35
125	0.075	0.1	31.32	1.20	0.43
125	0.1	0.15	45.64	1.25	0.44

Table 4. Taguchi L_9 orthogonal array and the observed response values using uncoated carbides

Cutting Speed (m/min)	Feed rate (mm/rev)	DOC (mm)	Cutting Force (N)	Surface Roughness (µm)	Tool Wear (mm)
75	0.05	0.1	27.5	1.22	0.40
75	0.075	0.15	35.53	1.31	0.42
75	0.1	0.2	43.85	1.42	0.44
100	0.05	0.15	26.22	1.15	0.41
100	0.075	0.2	34.54	1.29	0.45
100	0.1	0.1	44.04	1.40	0.48
125	0.05	0.2	26.43	1.14	0.47
125	0.075	0.1	31.2	1.37	0.50
125	0.1	0.15	44.77	1.46	0.53

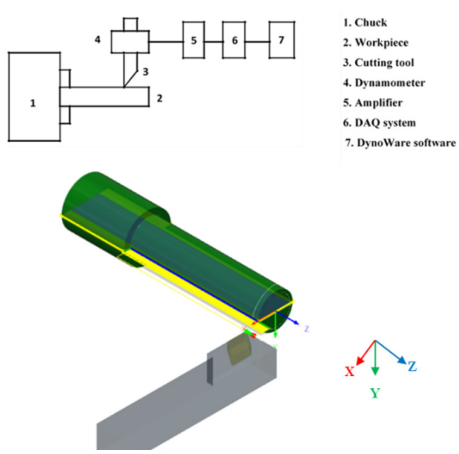

Fig 2. (a) schematic diagram of experimental set up; (b) tool path and cutting force direction

4.1 Taguchi analysis

4.1.1 Effects of machining parameters on cutting force, surface roughness and tool wear using coated carbides

Table 5-7 represent that the most influencing machining parameter on cutting force, surface roughness and tool wear during turning of CFRP with coated carbide is the feed rate (Rank 1 in each table). Similar result was found in the literature [4]. Figure 3 shows the effects of machining parameters on response characteristics. Higher cutting speed lowers the material removal rate due to the decreased contact area between workpiece and cutting tool which ultimately results in a lower cutting force. Higher cutting speed also reduces the contact length between chips and cutting tool which leads to a reduced friction in the machining surface [11]. As a result, the fiber fracture and the fiber pulling out get decreased, hence the surface roughness decreases. However, the increase of cutting speed beyond the optimal point increases the machine tool vibration which increases the surface roughness eventually. Increased cutting speed and feed rate increases the friction in machining surface and the vibration of the workpiece material leading to an increase of tool wear. Higher feed rate increases the contact area between workpiece and cutting tool leading to a higher material removal rate which results in an increase of cutting force and feed force. The increased feed force increases the fiber fracture and fiber pulling out on the outside surface of the workpiece materials leading to an increase of surface roughness. Similar outputs have been found in the literature [11]. Higher depth of cut results in a higher material removal rate and increased friction between cutting tool and workpiece. As a result, the cutting force increases. Turning operation of CFRP usually produces powder like chips and the higher depth of cut reduces the chance of friction between the chips and cutting tool which leads to a decrease of overall tool wear and surface roughness.

Table 5. Response table for means of cutting force (coated carbides)

Level	Means of Cutting Force (N) for corresponding parameter level		
	Cutting Speed	Feed rate	Depth of Cut
1	35.92	27.34	34.28
2	35.30	33.80	35.88
3	34.42	44.51	35.49
Max-min	1.50	17.16	1.59
Rank	3	1	2

Table 6. Response table for means of surface roughness (coated carbides)

Level	Mean of Surface Roughness (µm) for corresponding parameter level		
	Cutting Speed	Feed rate	Depth of Cut
1	1.180	1.126	1.188
2	1.168	1.186	1.181
3	1.192	1.228	1.171
Max-min	0.024	0.101	0.017
Rank	2	1	3

Table 7. Response table for means of tool wear (coated carbides)

Level	Mean of Tool Wear (mm) for corresponding parameter level		
	Cutting Speed	Feed rate	Depth of Cut
1	0.3647	0.3407	0.3903
2	0.3770	0.3900	0.3817
3	0.4070	0.4180	0.3767
Max-min	0.0423	0.0773	0.0137
Rank	2	1	3

In table 8-10, the highest S/N ratio represents the least variation between expected value and measured value of an output characteristic. From figure 4, it was observed that the highest S/N ratio obtained for cutting force are cutting speed at 125 m/min, feed rate at 0.05 mm/rev and depth of cut at 0.1 mm, respectively. So, the optimal machining parameters to obtain lower cutting force were predicted by Taguchi method as v=125 m/min, f=0.05 mm/rev, and DoC=0.1 mm. Similarly, the optimal machining parameters for obtaining lower surface roughness were predicted based on the highest S/N ratio as v=100 m/min, f=0.05 mm/rev, and DoC=0.2 mm. The optimal machining parameters to obtain lower tool wear was predicted as v=75 m/min, f=0.05 mm/rev, and DoC=0.2 mm. The corresponding level values for optimal parameters were bolded in tables 8-10.

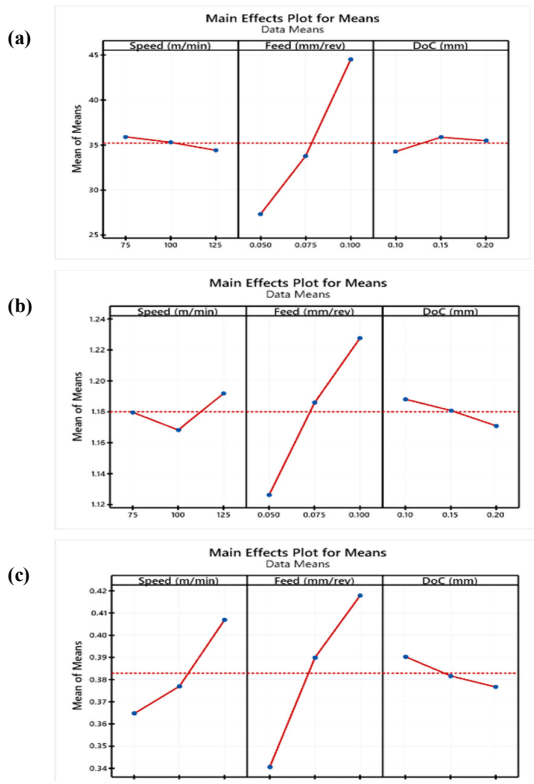

Fig 3. Effects of machining parameters on (a) cutting force; (b) surface roughness; (c) tool wear; (coated carbides)

Table 8. Response table for S/N ratio of cutting force (coated carbides)

Machining parameters	S/N ratio Level 1	Level 2	Level 3	Max-Min	Rank
v	-30.96	-30.81	**-30.50**	0.45	2
f	**-28.73**	-30.57	-32.97	4.23	1
DoC	**-30.56**	-30.91	-30.80	0.35	3

Table 9. Response table for S/N ratio of surface roughness (coated carbides)

Machining parameters	S/N ratio Level 1	Level 2	Level 3	Max-Min	Rank
v	-1.433	**-1.344**	-1.517	0.173	2
f	**-1.032**	-1.481	-1.781	0.749	1
DoC	-1.494	-1.434	**-1.366**	0.128	3

Table 10. Response table for S/N ratio of tool wear (coated carbides)

Machining Parameters	S/N ratio Level 1	Level 2	Level 3	Max-Min	Rank
v	**8.789**	8.498	7.854	0.935	2
f	**9.356**	8.201	7.584	1.772	1
DoC	8.226	8.421	**8.494**	0.269	3

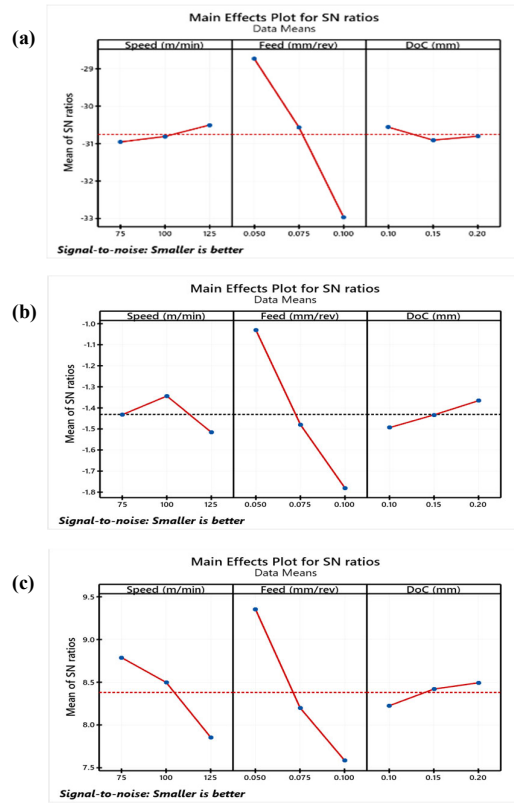

Fig 4. Main effect plot of S/N ratio for (a) cutting force; (b) surface roughness; (c) tool wear; (coated carbides)

4.1.2 Effects of machining parameters on cutting force, surface roughness and tool wear using uncoated carbides

Table 11-13 represent that the most influencing machining parameter for cutting force and surface roughness was the feed rate (Rank 1 in table 11 & 12) while the most influencing parameter for tool wear was cutting speed (Rank 1 in table 13). Similar results have been found in literature [4]. Figure 5 illustrates the effects of machining parameters on response characteristics for uncoated carbides. With the increase of cutting speed the contact area between workpiece and cutting tool decreases which reduces the material removal rate and the friction on machining surface leading to a decrease of cutting force. Lower friction in machining surface reduces the fiber fracture and the fiber pulling out, therefore the surface roughness decreases. However, the increase of cutting speed beyond the optimal point increases the machine tool and workpiece vibration which increases the surface roughness eventually. Workpiece vibration and the friction in the machining interface induced by higher cutting speed increase the cutting zone temperature. As a result, the tool wear increases. Higher feed rate and depth of cut increases the

material removal rate due to the increased contact area between workpiece and tool material which increases the friction on the machining interface. As a result, the cutting force and feed force increase. The increased feed force increases the fiber fracture and fiber pullout on the outside surface of the workpiece materials leading to an increase of surface roughness and tool wear. While turning the CFRP composites the powder like chips are generated which get attached to the surface of workpiece. Higher depth of cut reduces the friction between these chips and cutting tool which leads to a decrease in surface roughness. With the increase of depth of cut the cutting force as well as the contact area between workpiece and cutting tool increase which result in an increased tool wear.

Table 11. Response table for means of cutting force (uncoated carbides)

Level	Means of Cutting Force (N) for corresponding parameter level		
	Cutting Speed	Feed rate	Depth of Cut
1	35.63	27.05	34.58
2	35.60	34.09	36.17
3	34.13	44.22	34.61
Max-min	1.49	17.17	1.59
Rank	3	1	2

Table 12. Response table for means of surface roughness (uncoated carbides)

Level	Means of Surface Roughness (µm) for corresponding parameter level		
	Cutting Speed	Feed rate	Depth of Cut
1	1.317	1.172	1.334
2	1.282	1.325	1.310
3	1.325	1.427	1.281
Max-min	0.044	0.255	0.053
Rank	3	1	2

Table 13. Response table for means of tool wear (uncoated carbides)

Level	Means of Tool Wear (mm) for corresponding parameter level		
	Cutting Speed	Feed rate	Depth of Cut
1	0.4300	0.4263	0.4590
2	0.4463	0.4603	0.4563
3	0.4987	0.4883	0.4597
Max-min	0.0687	0.0620	0.0033
Rank	1	2	3

Table 14. Response table for S/N ratio of cutting force (uncoated carbides)

Machining Parameters	S/N ratio Level 1	Level 2	Level 3	Max-Min	Rank
v	-30.88	-30.88	**-30.43**	0.46	2
f	**-28.63**	-30.65	-32.91	4.28	1
DoC	**-30.61**	-31.01	-30.57	0.44	3

Table 15. Response table for S/N ratio of surface roughness (uncoated carbides)

Machining Parameters	S/N ratio Level 1	Level 2	Level 3	Max-Min	Rank
v	-2.378	**-2.129**	-2.400	0.271	3
f	**-1.378**	-2.440	-3.088	1.710	1
DoC	-2.485	-2.305	**-2.116**	0.369	2

Table 16. Response table for S/N ratio of tool wear (uncoated carbides)

Machining Parameters	S/N ratio Level 1	Level 2	Level 3	Max-Min	Rank
v	**7.343**	7.024	6.055	1.288	1
f	**7.425**	6.755	6.242	1.183	2
DoC	6.800	**6.870**	6.752	0.118	3

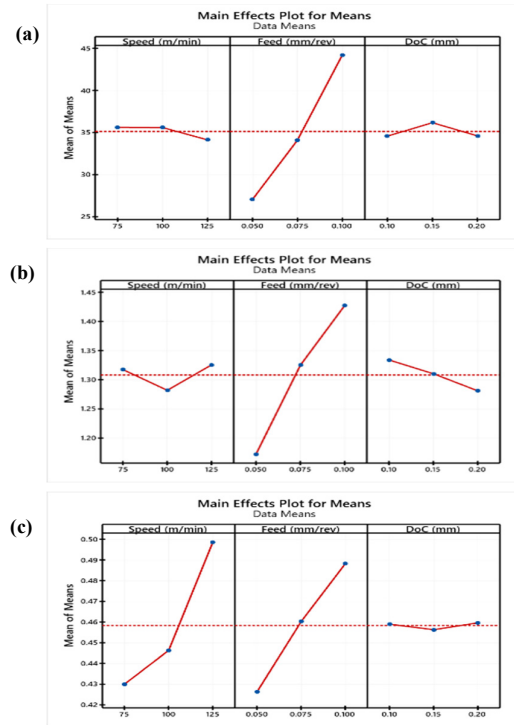

Fig 5. Effects of machining parameters on (a) cutting force;(b) surface roughness;(c) tool wear; (uncoated carbides)

In table 14-16, highest S/N ratio represents the least variation between expected value and measured value of an output characteristic. From figure 6, it was observed that the highest S/N ratio obtained for cutting force are cutting speed at 125 m/min, feed rate at 0.05 mm/rev and depth of cut at 0.1 mm. So, the optimal machining parameters to obtain lower cutting force were predicted by Taguchi method as v=125 m/min, f=0.05 mm/rev, and DoC=0.1 mm. Similarly, the optimal machining parameters to obtain lower surface roughness were predicted based on highest S/N ratio as v=100 m/min, f=0.05 mm/rev and DoC=0.2 mm. The optimal machining parameters to obtain lower tool wear were v=75 m/min, f=0.05 mm/rev, and DoC=0.15 mm. The corresponding level values of the optimal parameters were bolded in table 14-16.

4.2 Linear regression model

Linear regression analysis was performed using Minitab 19 software to develop mathematical models for cutting force, tool wear and surface roughness as a function of cutting speed, feed rate and depth of cut. Normal probability plot of residuals (distance between the observed value and the fitted value) has been used to measure the significance of coefficients in the models. A straight line in the residual plot indicates that the observed values are close to the fitted values and the coefficients in the model are statistically significant.

It was observed that both R^2 and R^2 (adj) values are very high for cutting force, tool wear and surface roughness models obtained from our linear regression analysis for both

coated and uncoated carbides which indicate that the models can be used significantly to predict the output characteristics. The normal probability plot of residuals for cutting force, surface roughness and tool wear have been shown in figure 7 & 8. It was observed that the residuals are very close to the fitted regression lines which indicate that the coefficients in the models are statistically significant.

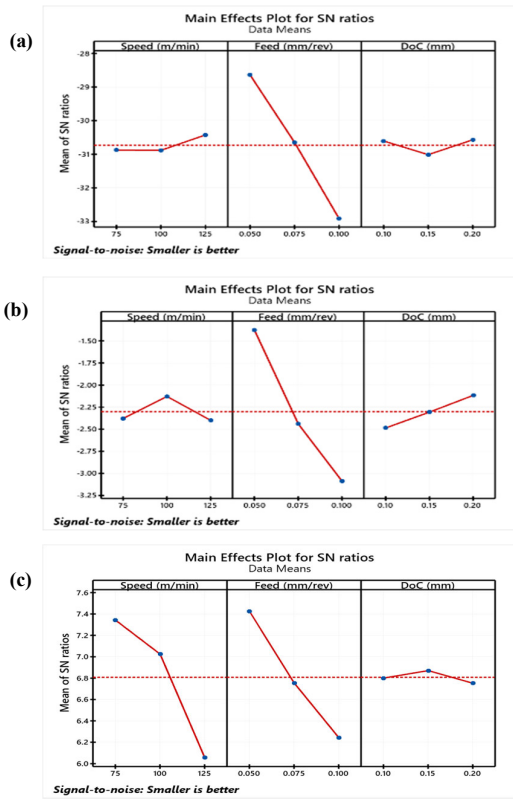

Fig 6. Main effect plots of S/N ratio for (a) cutting force;(b) surface roughness; (c) tool wear; (uncoated carbides)

Linear regression models for coated carbides are as follows-

$$\text{Cutting force}\left(F_c\right) = 10.66 - 0.0299 \times v + 343.3 \times f + 12.0 \times DoC$$
$$R^2 = 96.06\,\%;\ R^2(adj) = 93.93\,\%$$
$$\text{Surface Roughness}\left(R_a\right) = 1.0291 + 0.000245 \times v + 2.030 \times f - 0.173 \times DoC$$
$$R^2 = 93.37\,\%\ ;\ R^2(adj) = 89.39\,\%$$
$$\text{Tool wear} = 0.2027 + 0.000847 \times v + 1.547 \times f - 0.137 \times DoC$$
$$R^2 = 93.87\,\%;\ R^2(adj) = 90.19\,\%$$

Linear regression models for uncoated carbides are as follows-

$$\text{Cutting Force}\left(F_c\right) = 10.59 - 0.0299 \times v + 350.1 \times f + 6.9 \times DoC$$
$$R^2 = 97.17\,\%;\ R^2(adj) = 95.47\,\%$$
$$\text{Surface Roughness}\left(R_a\right) = 0.9891 + 0.000163 \times v + 5.094 \times f - 0.529 \times DoC$$
$$R^2 = 93.87\,\%;\ R^2(adj) = 90.20\,\%$$
$$\text{Tool wear} = 0.2230 + 0.001553 \times v + 1.127 \times f - 0.05 \times DoC$$
$$R^2 = 95.65\,\%;\ R^2(adj) = 93.03\,\%$$

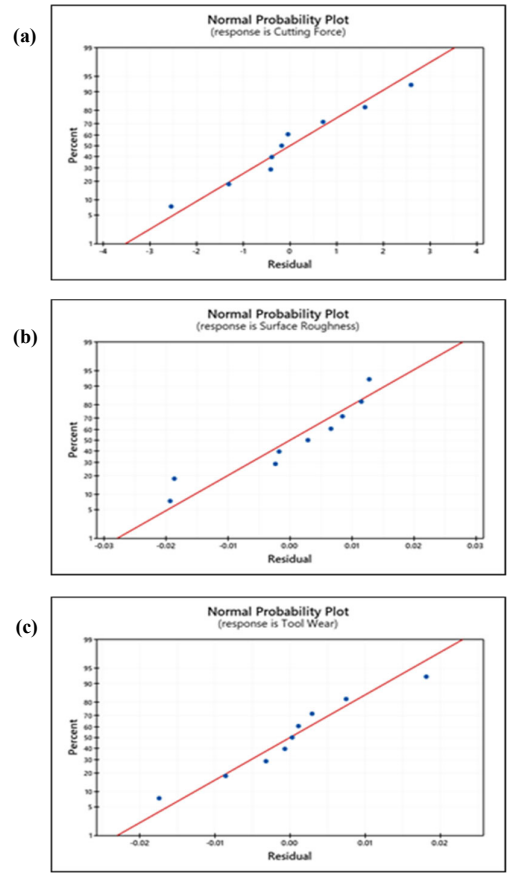

Fig 7. Normal probability plot of residuals for (a) cutting force; (b) surface roughness; (c) tool wear; (coated carbides)

4.3 Multi-objective Optimization using Multi-Objective Genetic Algorithm

Multi-objective Genetic Algorithm was applied to perform the multi-objective optimization using Multi-objective GA solver (gamultiobj) in MATLAB 2020. This solver returns a set of non-dominated optimal solutions as outcomes of multi-objective optimization process which are called pareto optimal solutions or Paretian points. The Paretian points obtained from the optimization process were plotted in a graph and the knee point was selected as the optimal solution of the multi-objective optimization process. At first the multi-objective optimization was performed using two different objective functions such as cutting force-surface roughness, cutting force-tool wear, and surface roughness-tool wear. Then multi-objective optimization was performed using three different objective functions- cutting force, tool wear and surface roughness. The goal of this study was to find the optimal combination of machining parameters to minimize the set of objective functions simultaneously and then compare the optimal parameters between coated and uncoated carbides. Table 17 shows the parameters used in the optimization process with GA:

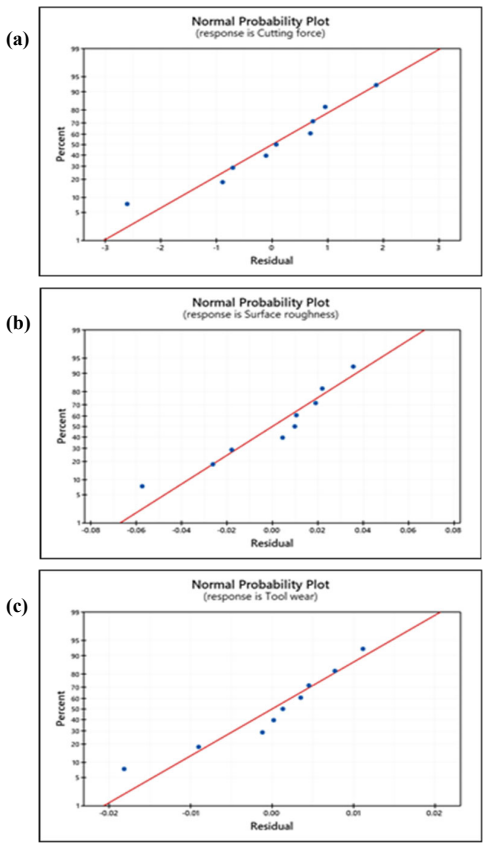

Fig 8. Normal probability plot of residuals for (a) cutting force; (b) surface roughness; (c) tool wear; (uncoated carbides)

Table 17. Parameters for GA

Parameter Name	Parameter Value
Population Size	50
Maximum no of generation	1000
Selection function	Tournament selection
Elite count	2
Crossover fraction	0.8
Crossover function	Constraint dependent
Mutation fraction	0.2
Mutation function	Constraint dependent
Number of parameters	3

4.3.1 Multi-objective optimization of cutting force and surface roughness

Table 18-19 show the Paretian points obtained from multi-objective optimization of cutting force and surface roughness using coated and uncoated carbides respectively and figure 9 shows the pareto front curve plotted using these Paretian points. From the graphs it can be found that the optimal condition for coated carbide is cutting force 27.22 N, surface roughness 1.121 µm with the cutting speed 97.67 m/min, feed rate 0.05 mm/rev and depth of cut 0.19 mm. The optimal condition for uncoated carbide is cutting force 25.73 N, surface roughness 1.160 µm with the cutting speed 124.57 m/min, feed rate 0.05 mm/rev, and depth of cut 0.20 mm. The corresponding optimal parameter values have been bolded in table 18-19.

Table 18. Paretian points obtained from multi-objective optimization of cutting force and surface roughness (coated carbides)

No.	Fc (N)	Ra (µm)	v (m/min)	f (mm/rev)	DoC (mm)
1	25.37	1.143	124.86	0.05	0.10
2	25.39	1.143	124.29	0.05	0.10
3	25.52	1.141	123.86	0.05	0.11
4	25.66	1.140	118.79	0.05	0.11
5	25.74	1.139	118.45	0.05	0.12
6	25.92	1.136	117.40	0.05	0.13
7	26.34	1.131	115.63	0.05	0.16
8	26.39	1.130	114.71	0.05	0.17
9	26.48	1.129	115.44	0.05	0.17
10	26.89	1.126	99.45	0.05	0.17
11	27.07	1.123	101.82	0.05	0.19
12	**27.22**	**1.121**	**97.67**	**0.05**	**0.19**
13	27.40	1.121	90.27	0.05	0.19
14	27.47	1.119	92.26	0.05	0.20
15	27.81	1.116	79.96	0.05	0.20
16	27.98	1.114	75.00	0.05	0.20

Table 19. Paretian points obtained from multi-objective optimization of cutting force and surface roughness (uncoated carbides)

No.	Fc (N)	Ra (µm)	v (m/min)	f (mm/rev)	DoC (mm)
1	25.05	1.211	125.00	0.05	0.10
2	25.20	1.200	124.93	0.05	0.12
3	25.29	1.195	124.32	0.05	0.13
4	25.41	1.184	124.98	0.05	0.15
5	25.45	1.181	124.77	0.05	0.16
6	25.54	1.178	123.18	0.05	0.16
7	25.60	1.170	124.73	0.05	0.18
8	**25.73**	**1.160**	**124.57**	**0.05**	**0.20**
9	25.89	1.159	119.39	0.05	0.20
10	26.07	1.158	113.10	0.05	0.20
11	26.24	1.156	108.16	0.05	0.20
12	26.27	1.156	107.16	0.05	0.20
13	26.41	1.156	101.97	0.05	0.20
14	26.41	1.155	102.41	0.05	0.20
15	26.56	1.155	97.25	0.05	0.20
16	26.61	1.154	95.74	0.05	0.20

4.3.2 Multi-objective optimization of cutting force and tool Wear

Table 21-22 show the Paretian points obtained from multi-objective optimization of cutting force and tool wear using coated and uncoated carbides respectively and figure 10 shows the pareto front curve plotted using these Paretian points. From the graphs it can be found that the optimal condition for coated carbide is cutting speed 76.56 m/min, feed rate 0.05 mm/rev and depth of cut 0.13 mm which provide the cutting force 27.13 N and tool wear 0.327 mm. The optimal condition for uncoated carbide is cutting force 26.42 N, tool wear 0.402 mm which is generated by cutting using speed 82.94 m/min, feed rate 0.05 mm/rev and depth of cut 0.11 mm.

4.3.3 Multi-objective optimization of surface roughness and tool wear

Table 20 shows the pareto optimal solution obtained from multi-objective optimization of surface roughness and tool wear for coated and uncoated carbides.

Table 20. Paretian points obtained from multi-objective optimization of surface roughness and tool wear

Carbides	Ra (µm)	T (mm)	v (m/min)	f (mm/rev)	DoC (mm)
Coated	1.114	0.316	75	0.05	0.2
Uncoated	1.150	0.386	75.00	0.05	0.2

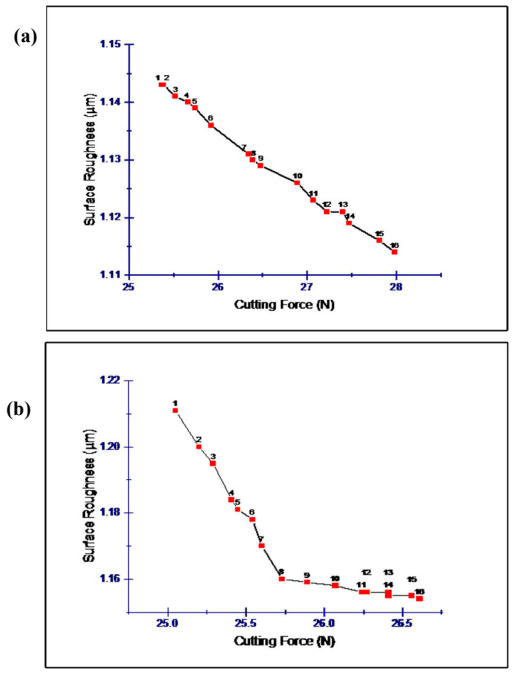

Fig 9. Pareto front of cutting force and surface roughness (a) coated carbides; (b) uncoated carbides

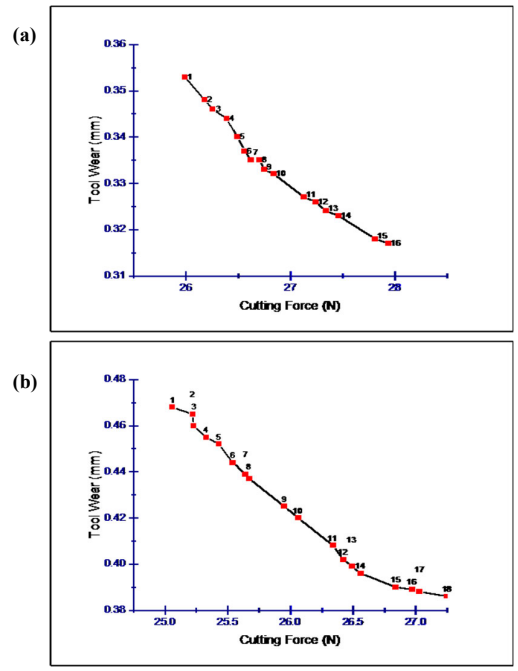

Fig 10. Pareto front of cutting force and tool wear for (a) coated carbides; (b) uncoated carbides

Table 21. Paretian points obtained from multi-objective optimization of cutting force and tool wear (coated carbides)

No.	Fc (N)	T (mm)	v (m/min)	f (mm/rev)	DoC (mm)
1	25.99	0.353	101.76	0.05	0.10
2	26.18	0.348	96.62	0.05	0.10
3	26.26	0.346	94.35	0.05	0.10
4	26.39	0.344	93.40	0.05	0.11
5	26.49	0.340	88.43	0.05	0.11
6	26.56	0.337	83.39	0.05	0.10
7	26.62	0.335	81.73	0.05	0.10
8	26.70	0.335	83.16	0.05	0.11
9	26.75	0.333	80.42	0.05	0.11
10	26.84	0.332	79.31	0.05	0.11
11	**27.13**	**0.327**	**76.56**	**0.05**	**0.13**
12	27.24	0.326	76.56	0.05	0.14
13	27.34	0.324	75.83	0.05	0.15
14	27.46	0.323	75.90	0.05	0.16
15	27.81	0.318	75.26	0.05	0.19
16	27.94	0.317	75.22	0.05	0.20

Table 22. Paretian points obtained from multi-objective optimization of cutting force and tool wear (uncoated carbides)

No.	Fc (N)	T (mm)	v (m/min)	f (mm/rev)	DoC (mm)
1	25.06	0.468	125.00	0.05	0.10
2	25.22	0.465	123.56	0.05	0.12
3	25.23	0.460	119.44	0.05	0.10
4	25.33	0.455	116.65	0.05	0.10
5	25.43	0.452	114.59	0.05	0.11
6	25.54	0.444	109.10	0.05	0.10
7	25.64	0.439	105.85	0.05	0.10
8	25.67	0.437	105.01	0.05	0.10
9	25.95	0.425	97.39	0.05	0.11
10	26.06	0.420	93.86	0.05	0.11
11	26.34	0.408	86.69	0.05	0.12
12	**26.42**	**0.402**	**82.94**	**0.05**	**0.11**
13	26.49	0.399	80.97	0.05	0.12
14	26.56	0.396	78.51	0.05	0.12
15	26.84	0.390	75.61	0.05	0.14
16	26.97	0.389	75.52	0.05	0.16
17	27.03	0.388	75.13	0.05	0.17
18	27.25	0.386	75.00	0.05	0.20

4.3.4 Multi-objective optimization of cutting force, surface roughness and tool wear

Table 23-24 show the pareto optimal points obtained from multi-objective optimization of cutting force, surface roughness and tool wear and figure 11 shows the Pareto front graph plotted using these pareto optimal points. The optimal condition for coated carbide is cutting force 27.21 N, surface roughness 1.121 µm and tool wear 0.366 mm using cutting speed 97.36 m/min, feed rate 0.05 mm/rev and depth of cut 0.19 mm. The optimal condition for uncoated carbide is cutting force 26.59 N, surface roughness 1.161 µm and tool wear 0.429 mm with cutting speed 102.42 m/min, feed rate 0.05 mm/rev and depth of cut 0.19 mm.

Table 23. Paretian points obtained from multi-objective optimization of cutting force, surface roughness and tool wear (coated carbides)

No.	Fc (N)	Ra (µm)	T (mm)	v (m/min)	f (mm/rev)	DoC (mm)
1	25.29	1.144	0.372	125.00	0.05	0.10
2	25.57	1.141	0.366	119.22	0.05	0.11
3	25.77	1.139	0.367	122.20	0.05	0.13
4	25.89	1.139	0.364	118.87	0.05	0.12
5	26.12	1.136	0.357	111.35	0.05	0.13
6	26.28	1.131	0.357	116.39	0.05	0.16
7	26.49	1.129	0.352	111.71	0.05	0.17
8	26.56	1.128	0.353	114.66	0.05	0.18
9	26.70	1.130	0.348	104.14	0.05	0.15
10	27.00	1.127	0.334	87.71	0.05	0.15
11	**27.21**	**1.121**	**0.336**	**97.36**	**0.05**	**0.19**
12	27.54	1.119	0.329	87.81	0.05	0.19
13	27.61	1.119	0.325	82.49	0.05	0.18
14	27.79	1.119	0.323	80.27	0.05	0.19
15	27.80	1.116	0.321	80.47	0.05	0.20
16	27.98	1.114	0.316	75.00	0.05	0.20

Table 24. Paretian points obtained from multi-objective optimization of cutting force, surface roughness and tool wear (uncoated carbides)

No.	Fc (N)	Ra (µm)	T (mm)	v (m/min)	f (mm/rev)	DoC (mm)
1	27.25	1.150	0.386	75.00	0.05	0.20
2	27.13	1.159	0.389	76.44	0.05	0.19
3	27.04	1.155	0.396	81.01	0.05	0.19
4	26.92	1.168	0.403	85.09	0.05	0.17
5	26.35	1.184	0.416	92.47	0.05	0.14
6	26.62	1.163	0.419	95.51	0.05	0.18
7	26.26	1.178	0.425	98.47	0.05	0.16
8	26.13	1.188	0.431	101.70	0.05	0.14
9	**26.59**	**1.161**	**0.429**	**102.42**	**0.05**	**0.19**
10	26.47	1.162	0.434	105.41	0.05	0.19
11	25.75	1.195	0.444	110.21	0.05	0.13
12	25.65	1.191	0.457	118.44	0.05	0.14
13	25.33	1.200	0.462	121.65	0.05	0.12
14	25.16	1.208	0.465	123.09	0.05	0.11
15	25.08	1.211	0.468	124.70	0.05	0.10
16	25.07	1.211	0.469	125.00	0.05	0.10

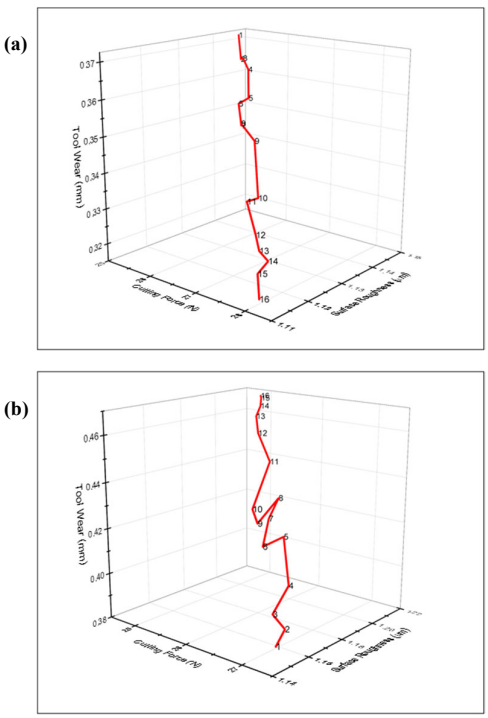

Fig 11. Pareto front of cutting force, surface roughness and tool wear for (a) coated carbides; (b) uncoated carbides

4.4 Validation for multi-objective optimization

Confirmation experiments have been performed for both coated and uncoated carbides to justify the results obtained from multi-objective optimization. It has been found that the experimental values are very close to the predicted values with a very lower percentage of error. So, the optimization results are reliable and valid. Table 25-26 represent the comparison between predicted and experimental values for coated and uncoated carbides respectively.

4.5 Comparative study of the machining parameters between coated and uncoated carbides

Table 27 shows that feed rate has the most significant effects on cutting force and surface roughness for both coated and uncoated carbides. Tool wear is mostly affected by feed rate in coated carbides while cutting speed is the most significant parameter for tool wear in uncoated carbides.

Table 25. Validation experiment results for optimal machining parameters using coated carbides

Response Characteristics	Cutting Parameters			Predicted			Experimental			Error (%)		
	v (m/min)	f (mm/rev)	DoC (mm)	Fc (N)	Ra (µm)	T (mm)	F(N)	Ra (µm)	T (mm)	Fc	Ra	T
Cutting Force & Surface Roughness	97.67	0.05	0.19	27.22	1.121		27.50	1.15		1.02	2.52	
Cutting Force & Tool Wear	75.56	0.05	0.13	27.13		0.327	27.81		0.336	2.44		2.68
Surface Roughness & Tool Wear	75	0.05	0.2		1.114	0.316		1.122	0.321		0.71	1.56
Cutting Force, Surface Roughness & Tool Wear	97.36	0.05	0.19	27.21	1.121	0.336	27.51	1.14	0.343	1.09	1.6	2.04

Table 26. Validation experiment results for optimal machining parameters using uncoated carbides

Response Characteristics	Cutting Parameters			Predicted			Experimental			Error (%)		
	v (m/min)	f (mm/rev)	DoC (mm)	Fc (N)	Ra (µm)	T (mm)	Fc (N)	Ra (µm)	T (mm)	Fc	Ra	T
Cutting Force & Surface Roughness	124.57	0.05	0.20	25.73	1.16		26.20	1.14		1.79	-1.75	
Cutting Force & Tool Wear	82.94	0.05	0.11	26.42		0.402	27.13		0.410	2.61		1.95
Surface Roughness & Tool Wear	75	0.05	0.2		1.15	0.386		1.17	0.392		1.71	1.53
Cutting Force, Surface Roughness & Tool Wear	102.42	0.05	0.19	26.59	1.161	0.429	27.15	1.15	0.415	2.06	-0.96	-3.37

Table 27. Most significant machining parameters for coated and uncoated carbides

Response Characteristics	Most Significant Machining Parameters	
	Coated Carbides	Uncoated Carbides
Cutting Force	Feed rate	Feed rate
Surface Roughness	Feed rate	Feed rate
Tool Wear	Feed rate	Cutting Speed

From table 28 we can see that uncoated carbide insert uses higher cutting speed and depth of cut and provides lower cutting force with higher surface roughness and tool wear in

optimized condition compared to those of coated carbide insert during turning of CFRP composites. This is because uncoated carbide generates higher friction on the machining surface during turning process. Since no coolant was used in this study, more heat gets concentrated on the cutting zone which leads to a decrease of cutting force and an increase of tool wear. When tool wear gets increased, a higher cutting speed in optimum level is necessary to minimize the surface roughness keeping the other response characteristics at an optimal level. There might also have some effects of coating material to resist the wear of tool in case of coated carbide inserts which provides lower tool wear despite having higher cutting force. Based on the comparative study of the optimized conditions between coated and uncoated carbides, it can be summarized that coated carbide is better for improved surface roughness and lower tool wear while uncoated carbide is better for lower cutting force during turning of CFRP composites.

Table 28. Comparison of optimal machining parameters for coated and uncoated carbide inserts

Responses	Carbides	Minimized Response Characteristics			Optimal Machining Parameters		
		Fc (N)	Ra (µm)	T (mm)	v (m/min)	f (mm/rev)	DoC (mm)
Cutting Force and Surface Roughness	Coated	27.22	1.121		97.67	0.05	0.19
	Uncoated	25.73	1.160		124.57	0.05	0.20
Cutting Force and Tool wear	Coated	27.13		0.327	76.56	0.05	0.13
	Uncoated	26.42		0.402	82.94	0.05	0.11
Surface Roughness and Tool wear	Coated		1.114	0.316	75	0.05	0.2
	Uncoated		1.150	0.386	75.00	0.05	0.2
Cutting Force, Surface Roughness and Tool wear	Coated	27.21	1.121	0.336	97.36	0.05	0.19
	Uncoated	26.59	1.161	0.429	102.42	0.05	0.19

5. Conclusion

Turning of CFRP composites has been studied based on Taguchi Analysis, Regression Analysis and Multi-Objective Genetic Algorithm using coated and uncoated carbide inserts. It was found that coated carbides provide lower surface roughness and tool wear while uncoated carbides provide lower cutting force. The most significant machining parameter during turning of CFRP composites using coated and uncoated carbides is the feed rate followed by cutting speed and depth of cut. The most significant parameter for tool wear in uncoated carbide is the cutting speed. In future work, the effects of cutting zone temperature on the surface roughness and tool wear will be investigated using different cutting tools. Moreover, the combined effects of cutting tool vibration and tool geometry on cutting force, surface roughness and tool wear can be investigated in our future research using algorithms such as Artificial Neural Network and Fuzzy Analysis.

Acknowledgements

The authors acknowledge the financial support provided by Dr. Subhash Bose, SSA Foundation, and UTRGV's Presidential Graduate Research Assistantship award to conduct this research.

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