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Research Article

Optimization and Investigation of the Initial Parameters Effects on Machining Forces in Aerial Graphite Part

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ABSTRACT

Graphite has recently received a lot of attention due to its numerous applications as well as its unique structure. Machining and machining conditions optimization are very important in reducing machining forces among other benefits. In this study, the effect of machining parameters such as spindle speed, cutting depth and feed rate on the machining forces was investigated and the optimization of these conditions was done to minimize the forces. This research uses the design of experiments to optimize the initial parameters to minimize machining forces. These experiments are based on the response surface method and analysis of variances used to identify the most effective factors in machining forces. The values of the primary parameters that provide the experiments design software are considered to be the spindle speed between 1000 and 3000 rpm, the feed rate between 1000 and 3000 mm/min, and the cutting depth between 3 and 9 mm. The results show that the machining forces increase by increasing the cutting depth and feed rate and decrease by increasing the spindle speed. The results obtained from the optimization also indicate that the machining forces reduced to their minimum value at the feed rate of 318.2072 mm/min, the cutting depth of 0.9546 mm and the spindle speed of 2356.7439 rpm.

1. Introduction

Graphite is a type of carbon that is crystalline. This material has many applications in the aerospace, military, electrical, nuclear and medical industries. Graphite has many properties such as thermal and electrical conductivity as well as very high machinability. Additionally, unlike diamonds, it has a soft and flexible structure. The end milling process is one of the most widely used processes in the industry. This operation can simply be used for a smooth and hard surface or parts with high complexity. High friction between the tool and the workpiece reduces the dimensional accuracy and surface quality of the products in this method. The selection of suitable machining conditions, as well as different levels of parameters, are very important in the quality of the production parts.

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Cutting speed, feed rate and cutting depth are machining parameters that greatly affect this process [1, 2]. Under different machining conditions, tool wear can affect surface smoothness, dimensional accuracy, temperature, machining force and power [3]. Simultaneously, the average roughness characteristics of a milled surface can be measured and the width dimensions at the bottom of the internal grooves can be checked. Therefore, the average surface roughness and size of internal grooves were selected as product quality objectives in this study. Lin and Chananda [4] optimized the quality of injection molding with an all-factorial design. In this study, the output parameters were optimized based on the input control. Puertas and Luis [5] used the experimental design method to optimize the machining parameters of the electrical discharge process. The tribological properties of graphite depend on the environment. Creating a layer of environmental pollution on the graphite surface affects its tribological performance [6]. The use of WC cutting tools with a special coating has improved the performance of graphite machining [7-9]. Cabral et al. [8] pointed out that tool wear in graphite machining is mainly more due to the abrasive nature of debris rather than as a result of localized heating of the cutting edge or machining parameters. Industrial graphite has good electrical and thermal conductivity characteristics and is resistant to temperatures up to 3000°C, due to the double connection through the hexagonal grid [10, 11]. There exist many studies on how chips are formed in graphite machining. Their findings showed that in graphite milling, the cut happens by a rupture process on the structure rather than the plastic deformation, which is due to its polycrystalline nature. In this process, small particles are formed, which leads to the production of powder instead of chips [8, 12, 13]. Xu et al. [14] examined the performance of coatings in graphite milling with a cutting speed of 300 meters per minute. Dehong et al. [15] experimentally investigated the machinability of micro-milling on fine-grained molded graphite. This operation is performed with 0.5 mm diamond coated, TiAlN-coated and uncoated tungsten carbide micro end mills tools. In this study, a standard central milling machine was used with a high-speed micro machining spindle. In order to perform the experiments and analysis of the machining process, Design of experiments (DOE) techniques were used. Surface properties of samples such as surface roughness, surface topography, and etc. were investigated using white light interferometry, SEM and a precision surface profiler. The effects of changes made in the cutting parameters such as feed rate, cutting speed, and cutting depth on surface roughness as well as surface damage were analyzed by using the ANOVA method. Experimental results show that the feed rate has the greatest effect on the surface roughness for all the tools and the diamond tool is not sensitive to cutting speed and cutting depth. Jiahui Niu et al. [16] examined the appropriate tools and parameters for compacted graphite iron machining. The use of compacted graphite iron to make automotive equipment such as diesel engine cylinder blocks and heads, due to its mechanical properties, has gradually replaced gray cast iron. This study investigated machining speed, feed per tooth, tool life, and surface characteristics with ceramic and carbide tools. The results revealed that the machining forces in using ceramic tools were more than carbide tools. The life of the tool as well as the quality of the sample surface increased with the use of ceramic tools. It is also important to note that the surface properties of the sample were strongly influenced by the used tools as well as the machining parameters. Bhiksha Gugulothu et al. [17] investigated the effect of water as a dielectric fluid and the concentration of graphite powder on the electric discharge machining of Ti-6Al-4V alloy. In this study, the Taguchi method was used to optimize the process parameters, including discharge current, pulse on time, pulse off time and graphite powder concentration. Moreover, the individual effect of process parameters on the performance characteristics were investigated. Analysis of variances (ANOVA) was also performed to identify the importance of the parameters on the measured response. More experimental models were developed by performing nonlinear regression analysis to predict process performance characteristics. Confirmation tests were performed in the relevant optimal parametric settings to confirm the predicted optimal values of performance characteristics. Juan Lu et al. [18] investigated the compacted graphite cast iron surface roughness using Gaussian process regression with square exponential covariance function. The results showed that the cutting speed and feed rate had the greatest effect on the surface roughness, and the cutting depth had a small effect on the surface roughness. Experimental results and statistical analysis indicate good agreement between the data. Yongchuan Lin et al. [19] investigated the effect of cutting speed, feed rate, and cutting depth on surface roughness and machining forces in graphite iron milling and optimized this process using the response surface method. The results showed that the cutting depth affects both machining forces and surface roughness and the feed rate only affects the machining forces and the cutting speed affects the surface roughness. In another study by Oliveira et al. [20], Cu-5 wt.% graphite milling under argon atmosphere conditions was studied for over 50 h to investigate the effect of milling time on the size and dispersion of copper and carbon phases. The powders were collected at different times and examined by X-ray diffraction (XRD), scanning electron microscopy (SEM and FESEM) and transmission electron microscopy (TEM). After 50 h of milling, the copper phase had a crystallite size of 24 nm and a micro-strain of 0.26%. No carbon deposition was observed when the composite was annealed at 600°C for 1 h in an argon atmosphere. These results indicate the lack of solid carbon solution in copper. Dayong Yang et al. [21] also investigated the surface roughness conditions in machined graphite/polymer composites. However, these composite models were prone to cracks and dents in machined surfaces.

The purpose of the present study is therefore to overcome the changes in the quality of the machined surface of graphite/polymer composites, to predict the surface roughness in different machining conditions and to optimize the process. Daneshfar et al. [22] investigated the effect of using graphite nozzles in engines on the amount of wear created in them. Mohammad Sakvand et al. [23] investigated the HfB_2-SiC-graphite composites. However, in this study, the effect of graphite on the microstructure was also investigated as were the changes in the weight and produced oxide layer. In fact, many studies have been done on the structures containing graphite and the effect of adding graphite to the structures. But, the present study tried to optimize the graphite machining process by examining the machining forces and an attempt has been made to reduce the forces. For this purpose, a dynamometer device was used, which simultaneously measures the forces during the machining process. Machining of graphite is very important and should be investigated in terms of its brittle structure.

2. Experimental Procedure

2.1. Materials and tools

In this study, the effects of cutting depth, feed rate, and spindle speed on the amount of machining forces in the graphite piece were investigated. A graphite block with dimensions of 20×30 cm was prepared to examine the effects of these parameters on the machining forces of the graphite piece. Due to the brittle nature of graphite, choosing the right tool is very important. Hence, after many studies, the inserted carbide tools were used to perform these experiments. In fact, dimensional accuracy and quality of the samples are highly impacted by the selected tools.

2.2. Design of experiments

Experimental designs used models to perform experiments to obtain accurate information about the factors under study. Nowadays, the required and accepted information is obtained through experimental designs and analysis of test data and facts about the studied factors are discovered through that information. In designing experiments, the most information is obtained with the least number of experiments. These methods also reduce the time and cost of testing. In this study, the central composite design method was used to design experiments by Design Expert software. These tests were designed to investigate the effect of primary parameters on machining forces in graphite milling (Table 1).

The range of the initial parameter was based on the studies conducted by others as well as the available equipment. The used design test table (Table 2) in this experiment, includes 20 tests that were designed based on the surface response method.

Table 1. Input parameters

Factor	Level
Feed rate (mm/min)	1000, 3000
Spindle speed (rpm)	1000, 3000
Cutting depth (mm)	3, 9

Table 2. Design of experiments

Feed rate (mm/min)	Cutting depth (mm)	Spindle speed (rpm)
2000	6	2000
2000	6	2000
318.21	6	2000
1000	3	3000
2000	6	2000
1000	9	3000
3000	9	1000
2000	6	2000
2000	11.0454	2000
2000	6	2000
2000	6	2000
2000	0.9546	2000
3000	3	3000
1000	9	1000
3000	9	3000
1000	3	1000
3681.79	6	2000
2000	6	318.21
3000	3	1000
2000	6	3681.79

2.3. Results of measuring machining forces

The designed tests in the previous step were performed separately on the prepared graphite piece for this test. As can be seen in Fig. 1, a dynamometer was used to measure the machining forces. This device includes a sensor that is installed under the part and measures the applied forces.

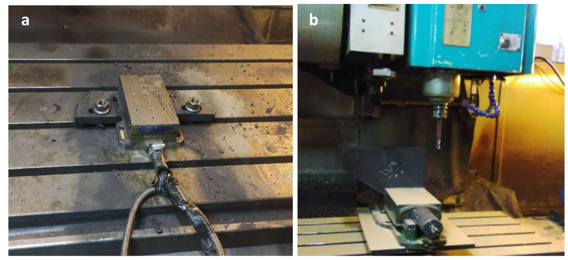

Fig. 1. Used equipment: (a) dynamometer sensor, and (b) method of closing the piece.

The force diagram of some experiments and results of the measurement forces are reported and illustrated in Fig. 2 and Table 3, respectively.

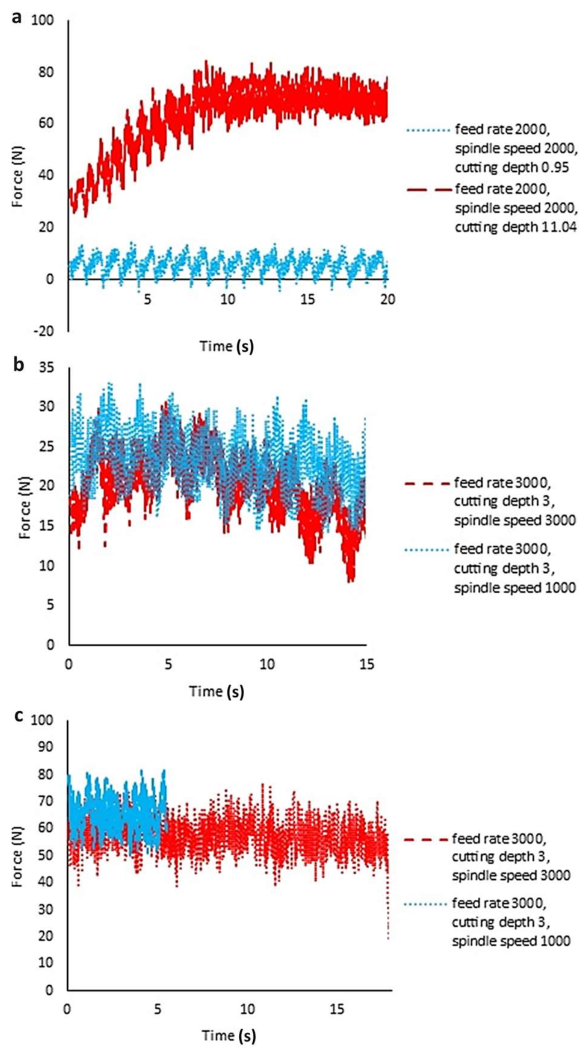

Fig. 2. Machining forces: (a) effect of cutting depth on the forces, (b) effect of spindle speed on the forces, and (c) effect of feed rate on the forces.

Table 3. Force results

Feed rate (mm/min)	Cutting depth (mm)	Spindle speed (rpm)	F_x (N)	F_y (N)	Force (N)
2000	6	2000	31	38	49
2000	6	2000	30.5	39	49.5
318.21	6	2000	20	30	36
1000	3	3000	7	8	11
2000	6	2000	31	38.5	50
1000	9	3000	21	74	77
3000	9	1000	70	101	123
2000	6	2000	30	38	48
2000	11.0454	2000	59	112	127
2000	6	2000	31	39	51
2000	6	2000	31.5	38	49
2000	0.9546	2000	4.5	3	5.5
3000	3	3000	15	6	16
1000	9	1000	79	109	135
3000	9	3000	39	56	68
1000	3	1000	38	25	46
3681.79	6	2000	19	22	29
2000	6	318.21	82	97	127
3000	3	1000	19	33	38
2000	6	3681.79	30	44	53

3. Results and Discussion

3.1. Analysis of variances

The analysis of variances of the applied forces to the tool are depicted in Tables 4, 5, and 6. The importance of each variable is determined by the P-Value, which is a measure of the deviation of the data from the mean value. Parameters of the model were regarded as statisticaly significant if they had a P-value less than 0.05.

Table 4. Analysis of variances for F_y (N)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	21467.1	2385.2	3582.41	0.000
Linear	3	18322.8	6107.6	9173.06	0.000
Feed rate	1	82.0	82.0	123.08	0.000
Cutting depth	1	14914.5	14914.5	22400.31	0.000
Spindle speed	1	3326.3	3326.3	4995.78	0.000
Square	3	2804.3	934.8	1403.94	0.000
Feed rate*Feed rate	1	294.4	294.4	442.23	0.000
Cutting depth*Cutting depth	1	631.0	631.0	947.64	0.000
Spindle speed*Spindle speed	1	1812.0	1812.0	2721.39	0.000
2-Way Interaction	3	340.0	113.3	170.22	0.000
Feed rate*Cutting depth	1	128.0	128.0	192.24	0.000
Feed rate*Spindle speed	1	50.0	50.0	75.10	0.000
Cutting depth*Spindle speed	1	162.0	162.0	243.31	0.000
Error	10	6.7	0.7		
Lack-of-Fit	5	5.4	1.1	4.51	0.062
Pure Error	5	1.2	0.2		
Total	19	21473.7			

Table 5. Analysis of variances for F_x (N)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	9139.58	1015.51	7462.03	0.000
Linear	3	6872.60	2290.87	16833.46	0.000
Feed rate	1	0.99	0.99	7.29	0.022
Cutting depth	1	3597.62	3597.62	26435.54	0.000
Spindle speed	1	3273.99	3273.99	24057.54	0.000
Square	3	1487.97	495.99	3644.57	0.000
Feed rate*Feed rate	1	232.56	232.56	1708.86	0.000
Cutting depth*Cutting depth	1	1.42	1.42	10.43	0.009
Spindle speed*Spindle speed	1	1138.33	1138.33	8364.56	0.000
2- Way Interaction	3	779.00	259.67	1908.05	0.000
Feed rate*Cutting depth	1	50.00	50.00	367.40	0.000
Feed rate*Spindle speed	1	364.50	364.50	2678.37	0.000
Cutting depth*Spindle speed	1	364.50	364.50	2678.37	0.000
Error	10	1.36	0.14		
Lack-of-Fit	5	0.03	0.01	0.02	1.000
Pure Error	5	1.33	0.27		
Total	19	9140.94			

Table 6. Analysis of variances for F_x (N)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	29144.6	3238.3	1366.94	0.000
Linear	3	24481.0	8160.3	3444.62	0.000
Feed rate	1	93.7	93.7	39.55	0.000
Cutting depth	1	18038.7	18038.7	7614.43	0.000
Spindle speed	1	6348.6	6348.6	2679.87	0.000
Square	3	4199.1	1399.7	590.84	0.000
Feed rate*Feed rate	1	497.0	497.0	209.78	0.000
Cutting depth*Cutting depth	1	529.2	529.2	223.40	0.000
Spindle speed*Spindle speed	1	3012.0	3012.0	1271.42	0.000
2-Way Interaction	3	464.5	154.8	65.36	0.000
Feed rate*Cutting depth	1	40.5	40.5	17.10	0.002
Feed rate*Spindle speed	1	32.0	32.0	13.51	0.004
Cutting depth*Spindle speed	1	392.0	392.0	165.47	0.000
Error	10	23.7	2.4		
Lack-of-Fit	5	18.5	3.7	3.55	0.095
Pure Error	5	5.2	1.0		
Total	19	29168.3			

The study of P-Value for machining forces indicated the validity of the proposed model in this research. As it is indicated, all the main factors are significant. The Pareto diagram is utilized for the proposed model. According to Figs. 3, 4, and 5, the cutting depth and the spindle speed had the greatest effect on the machining forces, respectively. It is also important to note that, among the interactive effects, the cutting depth and the spindle speed are effective in the machining forces.

Another used item for statistical analysis validation is the residual graphs that are shown in Figs. 6, 7, and 8. These graphs illustrate the normality of the test data and also indicate that the residuals do not follow a specific trend.

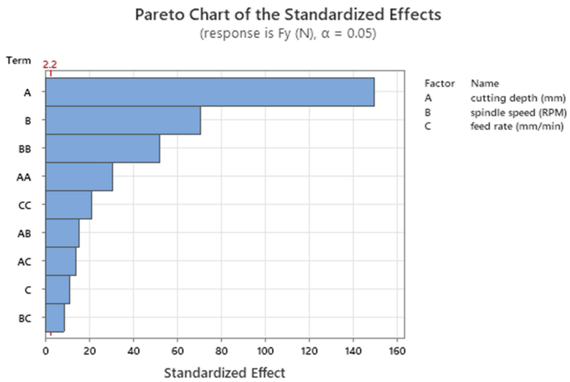

Fig. 3. Pareto chart for F_y (N).

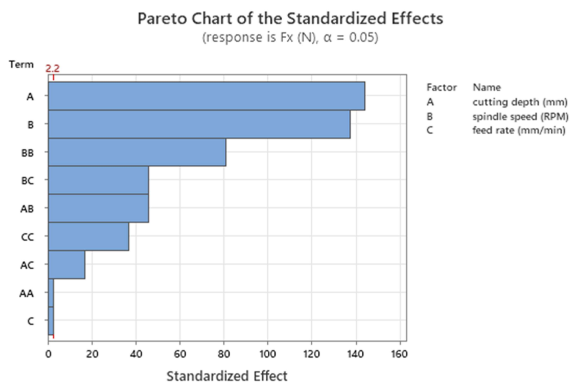

Fig. 4. Pareto chart for F_x (N).

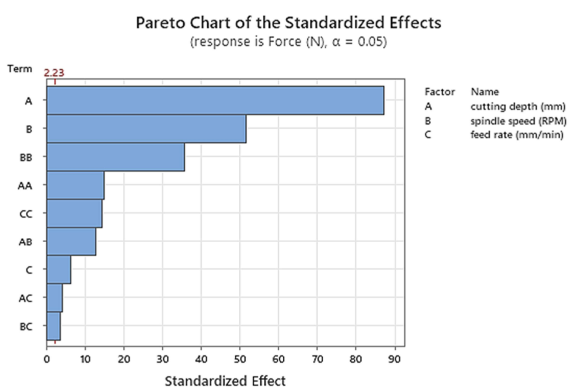

Fig. 5. Pareto chart for F (N).

3.2. Regression equation

A regression equation is used to predict the values of machining forces based on effective parameters. The values and coefficients of the variables in the model equation show the amount and effect of these variables, respectively. The equation is not coded; however, the desired force results can be obtained without performing the experiments and using these models. In fact, the necessary predictions can be made to perform the experiments by using these models.

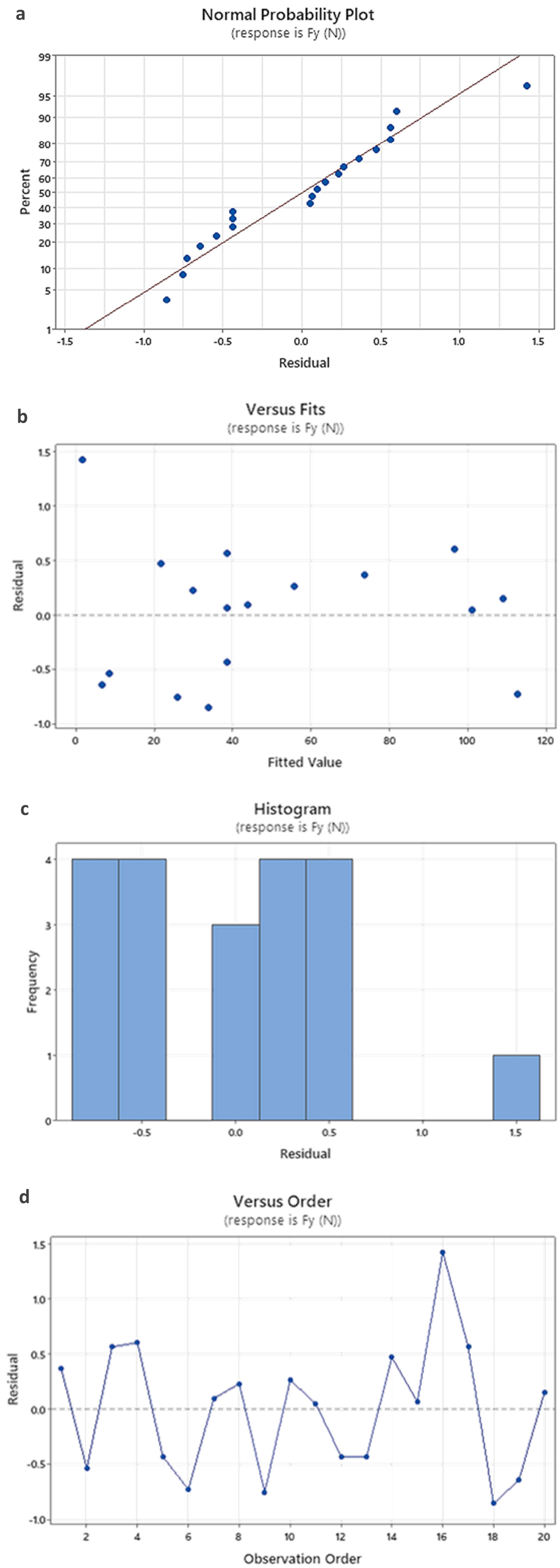

Fig. 6. Residual plot for F_y (N).

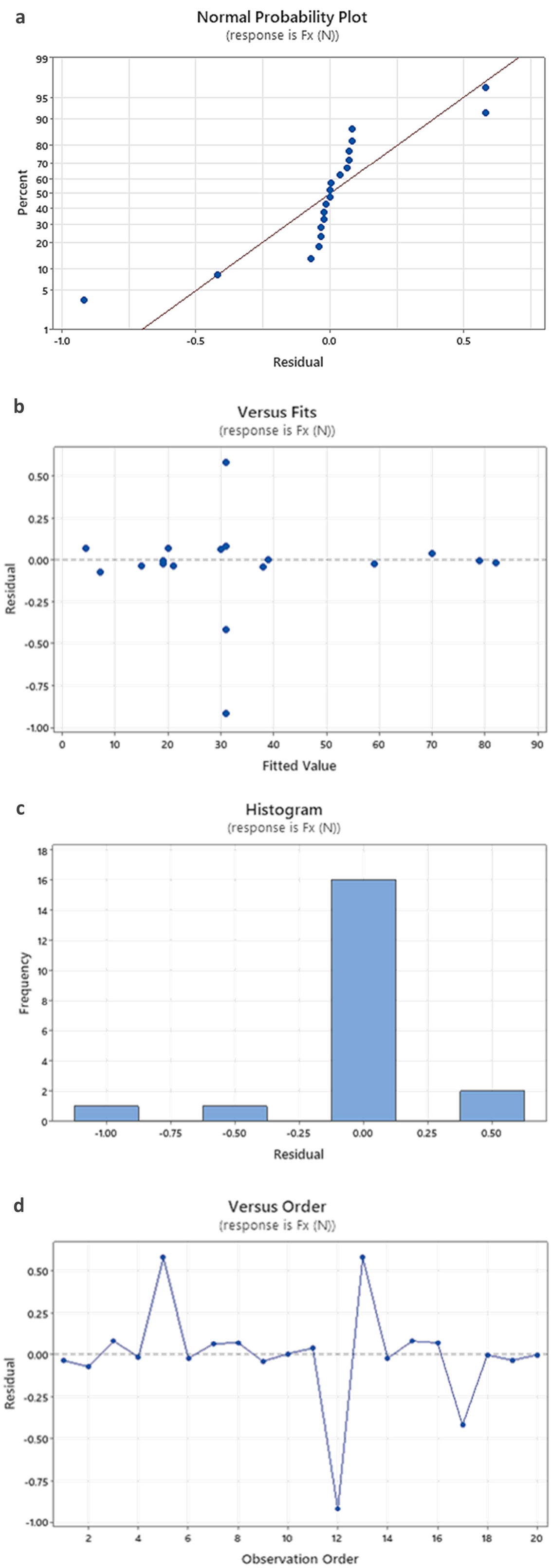

Fig. 7. Residual plot for F_x (N).

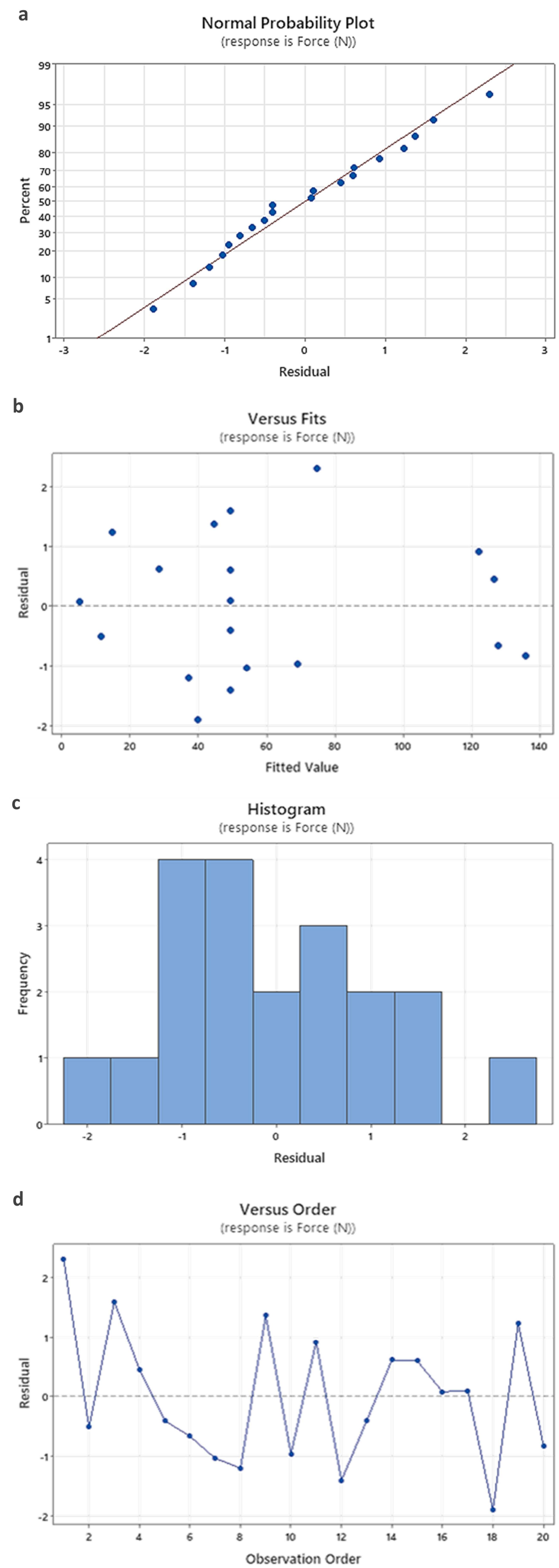

Fig. 8. Residual plot for F (N).

$$\begin{aligned} F_y &= 17.69 + 0.02863\, feed\ rate \\ &+7.860\, cutting\ depth \\ &-0.04646\, spindle\ speed \\ &-(0.000005\, feed\ rate) \times feed\ rate \\ &+0.7352\, cutting\ depth \times cutting\ depth \\ &+0.000011\, spindle\ speed \times spindle\ speed \\ &-0.001333\, feed\ rate \times cutting\ depth \\ &-0.000003\, feed\ rate \times spindle\ speed \\ &-0.001500\, cutting\ depth \times spindle\ speed \end{aligned} \tag{1}$$

$$\begin{aligned} F_x &= 60.62 - 0.002701\, feed\ rate \\ &+7.825\, cutting\ depth \\ &-0.051034\, spindle\ speed \\ &-0.000004\, feed\ rate \times feed\ rate \\ &+0.0349\, cutting\ depth \times cutting\ depth \\ &+0.000009\, spindle\ speed \times spindle\ speed \\ &+0.000833\, feed\ rate \times cutting\ depth \\ &+0.000007\, feed\ rate \times spindle\ speed \\ &-0.002250\, cutting\ depth \times spindle\ speed \end{aligned} \tag{2}$$

$$\begin{aligned} Force &= 64.65 + 0.02137\, feed\ rate \\ &+10.201\, cutting\ depth \\ &-0.06939\, spindle\ speed \\ &-0.000006\, feed\ rate \times feed\ rate \\ &+0.06733\, cutting\ depth \times cutting\ depth \\ &+0.000014\, spindle\ speed \times spindle\ speed \\ &-0.000750\, feed\ rate \times cutting\ depth \\ &+0.000002\, feed\ rate \times spindle\ speed \\ &-0.002333\, cutting\ depth \times spindle\ speed \end{aligned} \tag{3}$$

3.3. Investigating the effect of main factors on machining forces

The effects of the main factors on machining forces are shown diagrammatically in Figs. 9, 10, and 11. According to the diagrams, the machining forces increase with increasing cutting depth. The increase of the involved edge in the tool and workpiece causes this issue. As can be seen in the figures, the machining forces first increase and then decrease by increasing the spindle speed. In addition, with increasing the feed rate, the machining forces do not change much and go through an almost constant process.

As can be seen, the machining forces are reduced and the machining conditions are improved by reducing the cutting depth as well as increasing the spindle speed. The feed rate has little effect and can be ignored.

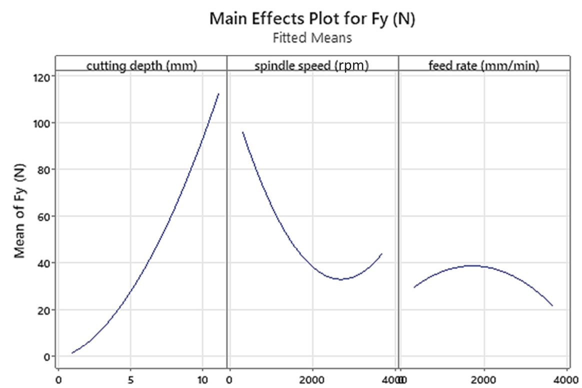

Fig. 9. The effects of each parameter on the F_y (N) (spindle speed (rpm), cutting depth (mm), feed rate (mm/min).

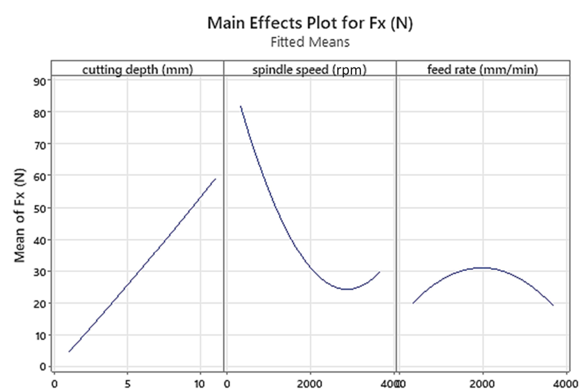

Fig. 10. The effects of each parameter on the F_x (N) (spindle speed (rpm), cutting depth (mm), feed rate (mm/min).

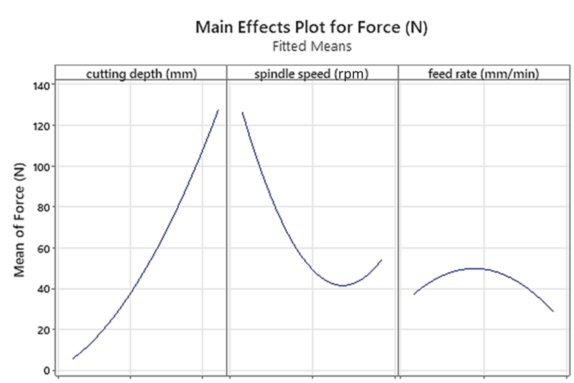

Fig. 11. The effects of each parameter on the F (N) (spindle speed (rpm), cutting depth (mm), feed rate (mm/min).

3.4. Interaction between the main factors

The interaction between the parameters can be seen in Figs. 12, 13, and 14. These diagrams illustrate the interaction of the parameters on the machining forces.

The results of studying the interaction of input parameters on machining forces are as follows:

Examining the diagrams shows that the machining forces increase by increasing the cutting depth and this is due to the increase in the length of the tool engaging with the workpiece and the amount of chips in front of the tool, which can also cause the tool to break. The diagrams show that machining forces reduce by increasing the spindle speed due to the increased chip removal and heat generation at the point of contact between the tool and the workpiece. Feed rate changes have little effect on forces and can be ignored.

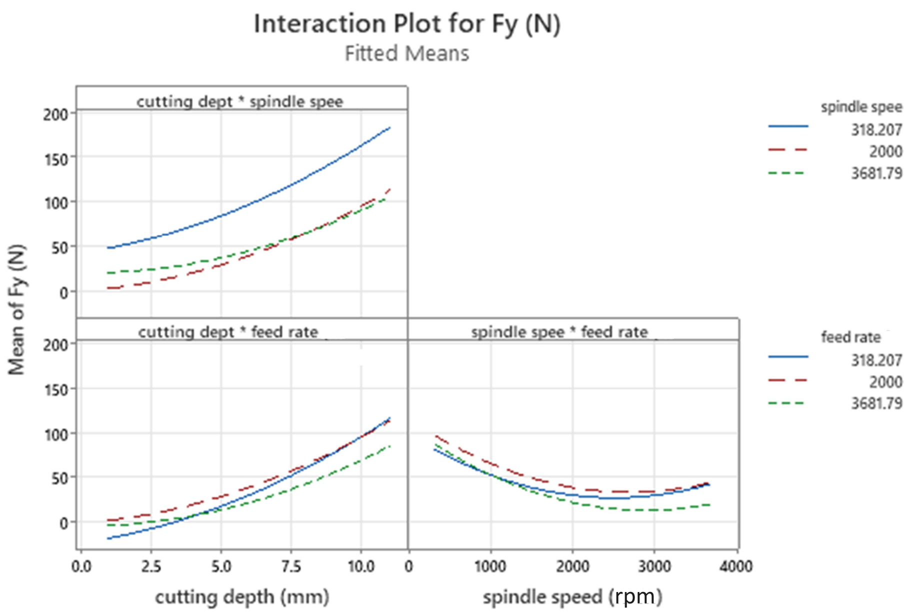

Fig. 12. The parameters interaction on the F_y (N) spindle speed (rpm), cutting depth (mm) and feed rate (mm/min).

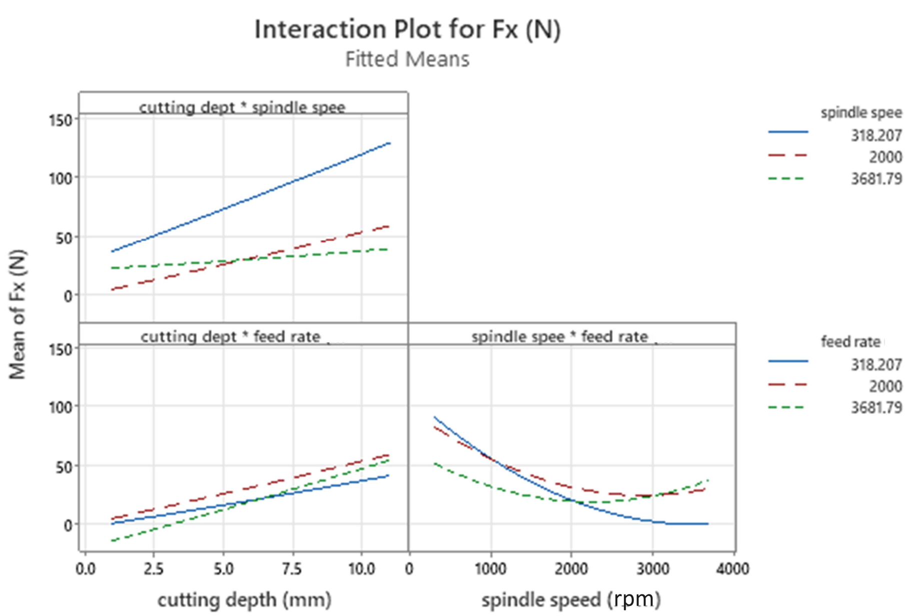

Fig. 13. The parameters interaction on the F_x (N) spindle speed (rpm), cutting depth (mm) and feed rate (mm/min).

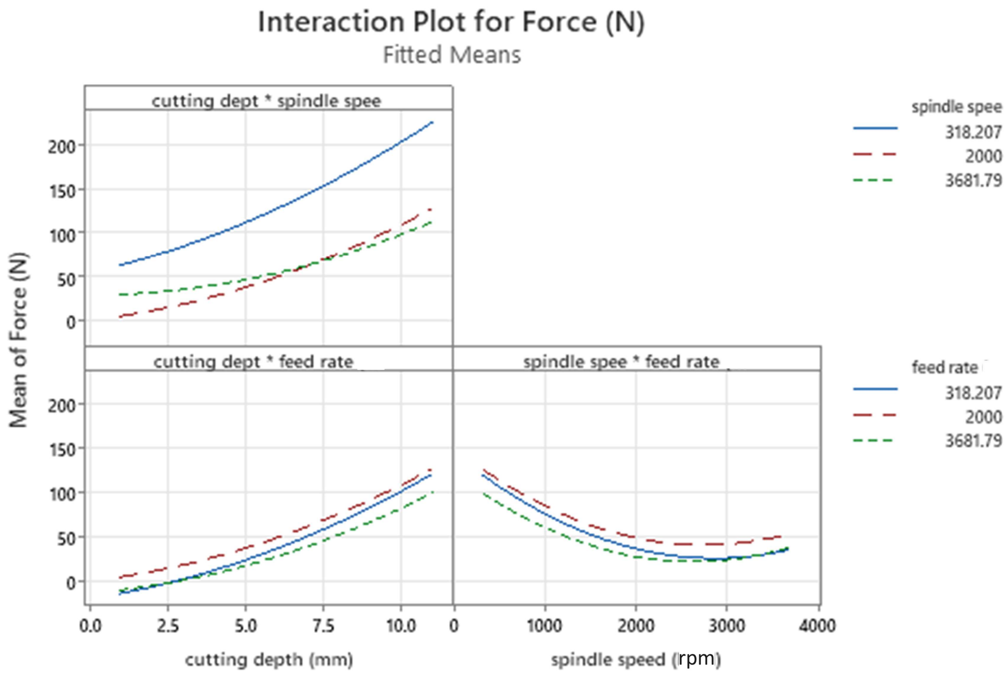

Fig. 14. The parameters interaction on the F (N) spindle speed (rpm), cutting depth (mm) and feed rate (mm/min)

3.5. Optimization

The purpose of optimization in this study is to investigate the initial parameters to minimize machining forces. The maximum and minimum values of the measured force for the above experiments design are based on Table 7.

Table 7. The minimum and maximum measured forces

Response	Goal	Lower	Target	Upper	Weight
F_y (N)	Minimum		3.0	112	1
F_x (N)	Minimum		4.5	82	1
Force (N)	Minimum		5.5	135	1

Machining forces are one of the parameters to check whether the workpiece is well machined or not. By selecting the least machining forces, machining conditions are improved. Depreciation of milling machine, tool wear, surface roughness and energy consumption are reduced by reducing machining forces.

The results of the optimization process (Fig. 15) indicate that the optimal state occurs when the forward speed is at its lowest value of 318.2072 mm/min, the cutting depth is at its lowest value of 0.9546 mm and the spindle rotation speed is 2356.7439 rpm.

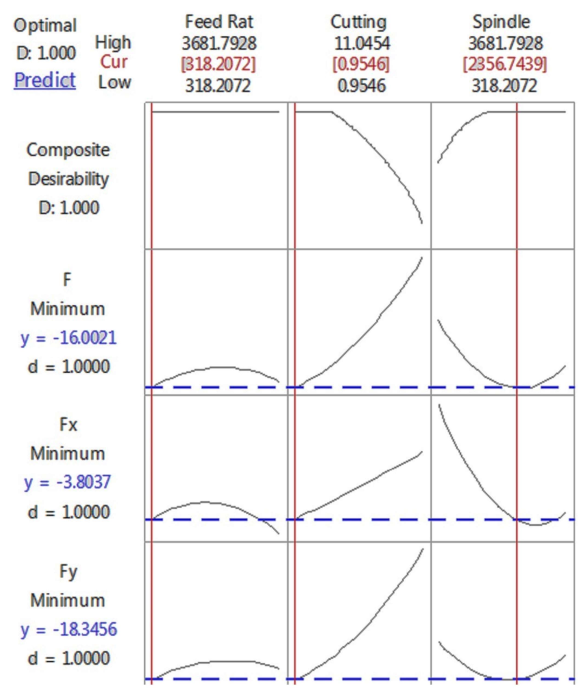

Fig. 15. The Influence of input parameters on the machining forces optimization (spindle speed (rpm), cutting depth (mm), feed rate (mm/min).

4. Conclusion

Graphite machining is very important because of the properties of this material. This study made use of samples with sensitive and complex geometry. The brittle nature of graphite parts causes micro-cracks as well as structural residual stresses. For this reason, the obtained results in this study are used to optimize the machining conditions of sensitive parts and reduce micro-cracks and residual stresses. In fact, it is the first time to examine the machining force of air graphite experimentally with special characteristics. The force results show the low value of force in graphite machining. The smallest change in machining conditions, coolant and ambient temperature cause drastic changes in the results. An increase in machining forces indicates the inappropriateness of the parameters and, as a result, the creation of micro-cracks. Therefore, in this study, the machining conditions of graphite parts were investigated and optimized to reduce machining forces. The obtained results are as follows:

- The machining forces increase with the increase in the cutting depth. The increase of the involved edge in the tool and workpiece causes this issue.
- The machining forces were reduced by increasing spindle speed, due to the heating of the connection point between the tool and the workpiece.
- Machining forces in working with graphite parts were very small due to the brittle nature of this material.
- The amount of machining forces increases with the increase in the feed rate. The increase in force in this case was very small and insignificant and can be ignored.
- The experiments were acceptable and hence the results can be cited according to the results obtained from the design of the experiments.
- Optimal state occurred when the forward speed was at its lowest value of 318.2072 mm/min, the cutting depth was at its lowest value of 0.9546 mm, and the spindle rotation speed was 2356.7439 rpm.
- Based on the optimization results, the maximum impact on the machining forces in graphite has a cutting depth and by increasing this parameter, the machining forces show the highest increase. The rotation speed of the spindle also has an acceptable effect and as the spindle speed increases, these forces decrease.

Conflict of Interests

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