



OPTIMIZATION OF MACHINING FORCES DURING HIGH-SPEED TURNING OF GRAYCAST IRON WITH CBN TOOLS BASED ON RESPONSE SURFACE METHODOLOGY

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ABSTRACT

To improve tool performance and productivity, high-speed machining of gray cast iron with cutting tools made of cubic boron nitride (CBN) has garnered considerable interest. The influence of cutting parameters, such as cutting speed, feed rate, and depth of cut, on the cutting force, feed force, and thrust force during CNC turning of gray cast iron was systematically investigated in this study. Response Surface Methodology (RSM) was used to organize and execute experiments to develop mathematical models that explain the relationship between the machining parameters and force components. Analysis of variance (ANOVA) was used to determine the significance of the individual and interaction effects of the process aspects. Followed by the depth of cut. In high-speed situations, the cutting speed has a relatively small impact. The RSM-developed quadratic regression models showed a strong agreement with the experimental data. An ideal set of machining settings was obtained by performing multi-objective optimization to simultaneously decrease the cutting, feed, and thrust forces.. The findings of this study provide valuable insights for optimizing the high-speed machining of graycast iron using CBN tools, leading to improved machining performance and reduced cutting forces.



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I. INTRODUCTION

Graycast iron is extensively used in automotive and industrial components because of its excellent damping capacity, good thermal conductivity, satisfactory machinability, and low production cost [1]. Typical applications of gray cast iron include engine blocks, brake discs, cylinder liners, and machine tool structures, where dimensional accuracy and productivity are critical [2]. The presence of graphite flakes in the microstructure of gray cast iron leads to non-uniform material behaviour during machining operations [3]. This heterogeneous microstructure causes fluctuations in the cutting forces and accelerates tool wear during turning and milling processes [4]. High-speed machining (HSM) has gained significant importance in modern manufacturing because of its ability to enhance productivity and reduce machining time [5]. In the machining of graycast iron, higher cutting speeds can promote thermal softening of the work material and reduce the chip-tool contact length [6]. Such effects may contribute to a reduction in cutting forces under high-speed conditions [7]. However, excessive cutting speeds combined with inappropriate feed rates or depths of cut can lead to rapid tool degradation and machining instability [8]. Cubic Boron Nitride (CBN) cutting tools are widely used for machining gray cast iron due to their superior hot hardness and excellent wear resistance [9]. CBN tools also exhibit high chemical inertness and thermal stability under dry and high-speed machining conditions [10]. Compared to coated carbide and ceramic tools, CBN tools show improved resistance to abrasive and adhesive wear when machining cast irons [11]. These characteristics make CBN tools particularly suitable for force-sensitive machining applications involving hard and abrasive materials [12]. Machining force components such as cutting force, feed force, and thrust force are key indicators of machining performance [13]. These force components directly influence tool wear, power consumption, vibration behaviour, surface finish, and dimensional accuracy of machined parts [14].

Previous studies have reported that feed rate and depth of cut are the most influential parameters affecting machining forces [15]. Cutting speed generally exhibits a comparatively lower influence on force components under high-speed machining regimes [16]. A popular statistical method for modelling and optimizing machining operations with several interacting parameters is Response Surface Methodology (RSM) [17]. RSM makes it possible to create empirical regression models that retain prediction accuracy while requiring less experimental work [18]. The integration of RSM with analysis of variance (ANOVA) allows identification of statistically significant factors and interaction effects [19]. RSM-based multi-objective optimization has been effectively used to concurrently reduce machining reactions including cutting forces and tool wear [20]. In the present study, CNC turning experiments were conducted on graycast iron using CBN cutting tools to investigate the effects of cutting speed, feed rate, and depth of cut on cutting, feed, and thrust forces. Quadratic regression models were developed using RSM and statistically validated through ANOVA to ensure model adequacy. Multi-objective optimization was performed to identify optimal machining conditions for minimizing force components [21]. Objectives of the present work:

- The search for the optimum cutting speed, feed, and depth of cut for turning operations in order to achieve a satisfactory surface finish is the goal of this particular effort.
- As a result, production time is shortened, which lowers costs and boosts output.

II. THEORETICAL REFERENCE

II.1 MATERIALS CHARACTERIZATION

The research, of the study, the material used was Cast Iron GG25, a graycast iron grade specified under EN 1561 [22], known for its lamellar graphite microstructure within a pearlitic matrix. It has a minimum tensile strength of 250 MPa and a Brinell hardness of 180–240 HB, offering excellent castability, machinability, and vibration damping due to high carbon and silicon content. GG25 is widely used for machine tool structures and automotive components requiring moderate strength and effective damping. The cutting tools were square-shaped CBN inserts conforming to ISO specifications SNKN 1204EN [23]. Machining forces were measured using a three-component piezoelectric dynamometer. The cutting force acts in the direction of cutting speed, influencing material removal and power consumption. The feed force acts along the feed direction, impacting tool deflection and surface finish. The thrust force acts perpendicular to the machined surface, affecting tool stability and vibration.

III. MATERIALS AND METHODS

Table 1 illustrates how the Box-behnken Design (BBD) was used to maximize graycast iron's high-speed machining parameters using CBN inserts. BBD is a response surface methodology (RSM) technique that minimizes the number of experimental runs while effectively assessing the effects of several independent variables on one or more response variables. Three machining parameters were chosen as independent variables in this study: depth of cut, feed rate, and cutting speed. The design combines variables at three levels (low, medium, and high) to create a set of experiments. Excluding extreme corner points, which reduces experimental costs and ensures safe operating conditions for high-speed machining. This method also allows the modelling of quadratic relationships and interactions between variables, facilitating the identification of optimal machining conditions for minimizing cutting forces and surface roughness.



Figure 1: Super prize 1650 N.C Lathe and Figure 2: Piezoelectric Dynamometer.
Source: Authors, (2026).

A three-component piezoelectric dynamometer installed on the lathe tool post, as seen in Fig. 2, was used to measure the machining forces. The cutting force controls material removal and power consumption while acting in the direction of cutting speed. While the thrust force operates perpendicular to the machined surface and influences tool stability and vibration, the feed force works along the feed direction and affects tool deflection and surface finish. The observed force components were utilized to create RSM-based predictive models and assess the impact of feed rate, depth of cut, and cutting speed.

Table 1: Process Parameters and Design of Experiments.

SL.No	Cutting speed (m/min)	Feed rate(mm/rev)	Depth of cut(mm)	Cutting force (N)	Feed force(N)	Thrust force(N)
1	180	0.16	0.25	65	124	106
2	30	0.12	0.5	4	19	10
3	105	0.12	0.25	54	89	96
4	30	0.12	0	9	32	19
5	105	0.12	0.25	10	37	39
6	105	0.16	0.5	50	109	95
7	105	0.12	0.25	43	98	90
8	30	0.16	0.25	34	48	14
9	105	0.16	0	40	90	70
10	180	0.12	0.5	68	96	95
11	180	0.08	0.25	52	60	78
12	30	0.08	0.25	13	34	27
13	105	0.12	0.25	58	117	98
14	180	0.12	0	65	124	106
15	105	0.08	0.5	13	34	23
16	105	0.08	0	18	47	60

Source: Authors, (2026).

Based on RSM analysis, an empirical regression model was developed to predict the forces as a function of cutting speed, feed rate, and depth of cut, as given in Eq. (1). (2) and (3).

$$F_f = 37.25 + 23.75V + 11.63f + 0.375d \quad (1)$$

$$F_c = -44.175 + 0.4517V + 612.5f - 17.5d \quad (2)$$

$$F_t = 64.13 + 39.38V + 12.13f - 4.0d \quad (3)$$

Table 2: ANOVA test results for Cutting force.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	14135.25	3	4711.75	8.84	0.0023	significant
A-cutting speed	9180.13	1	9180.13	17.22	0.0013	
B-feed	4802.00	1	4802.00	9.01	0.0110	
C-depth of cut	153.13	1	153.13	0.2873	0.6018	
Residual	6396.50	12	533.04			
Lack of Fit	2883.75	9	320.42	0.2736	0.9431	not significant
Pure Error	3512.75	3	1170.92			
Cor Total	20531.75	15				

Source: Authors, (2026).

Table 3: ANOVA test results for Feed force.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5594.75	3	1864.92	10.05	0.0014	significant
A-cutting speed	4512.50	1	4512.50	24.32	0.0003	
B-feed	1081.13	1	1081.13	5.83	0.0327	
C-depth of cut	1.13	1	1.13	0.0061	0.9392	
Residual	2226.25	12	185.52			
Lack of Fit	803.50	9	89.28	0.1883	0.9779	not significant
Pure Error	1422.75	3	474.25			
Cor Total	7821.00	15				

Source: Authors, (2026).

Table 4: ANOVA test results for thrust force.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	13707.25	3	4569.08	9.20	0.0020	significant
A-cutting speed	12403.13	1	12403.13	24.96	0.0003	
B-feed	1176.13	1	1176.13	2.37	0.1499	
C-depth of cut	128.00	1	128.00	0.2576	0.6210	
Residual	5962.50	12	496.87			
Lack of Fit	3603.75	9	400.42	0.5093	0.8099	not significant
Pure Error	2358.75	3	786.25			
Cor Total	19669.75	15				

Source: Authors, (2026).

Insignificant model terms were retained to maintain the hierarchical structure of the regression models, as recommended in Response Surface Methodology, as shown in Tables 2, 3, and 4. Eliminating these terms may distort the fitted response surface and adversely affect prediction accuracy within the design space. The overall model significance, with F-values of 8.84, 10.05, and 9.20 for the cutting force, feed force, and thrust force models, respectively, along with statistically insignificant lack-of-fit values ($F = 0.27, 0.19, \text{ and } 0.51$), confirms that the retained models adequately represent the experimental data. Therefore, the models are suitable for reliable prediction and process optimization.

IV. RESULTS AND DISCUSSIONS

The experimental findings show that cutting speed has a minor but important impact on machining forces, while feed rate and depth of cut are the primary factors. A rise in the feed rates leads to a pronounced rise in cutting, feed, and thrust forces due to increased chip thickness. Depth of cut primarily affects the cutting force by enlarging the shear plane area. Cutting speed influences force levels through combined mechanical and thermal effects, with moderate force escalation observed at higher speeds.

IV.1 INFLUENCE OF MACHINING PARAMETERS ON FORCES

- **Cutting Speed:** The experimental results as shown in Figure 2 indicate that cutting force, feed force, and thrust force generally increase with higher cutting speed. This rise is attributed to the work material's strain-rate sensitivity, increased tool-chip friction, and greater resistance to plastic deformation. Feed and thrust forces show more sensitivity to cutting speed variations [24], [25].
- **Feed Rate:** The results show in Figure 3 All three force components (cutting, feed, and thrust forces) markedly increase with a higher feed rate. This is primarily due to the increased uncut chip thickness and material removal rate. Feed and thrust forces are particularly sensitive to changes in feed rate.
- **Depth of Cut:** While feed rate and depth of cut are identified as primary factors affecting machining forces, depth of cut mainly influences the cutting force by increasing the shear plane area. The study also noted in the Fig.4 that minimal force values are observed at low cutting speed, low feed, and low depth of cut combinations, representing stable and energy-efficient machining conditions.

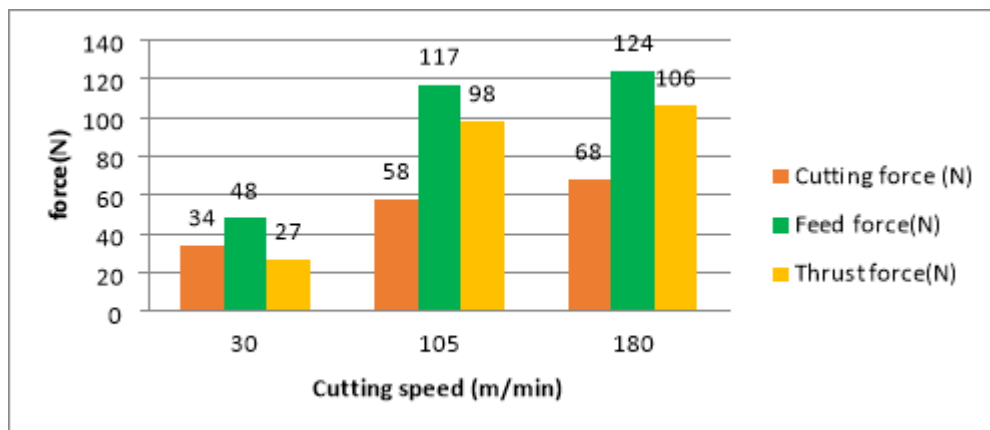


Figure 2: Cutting speed Vs cutting force, feed force, and thrust force.
Source: Authors, (2026).

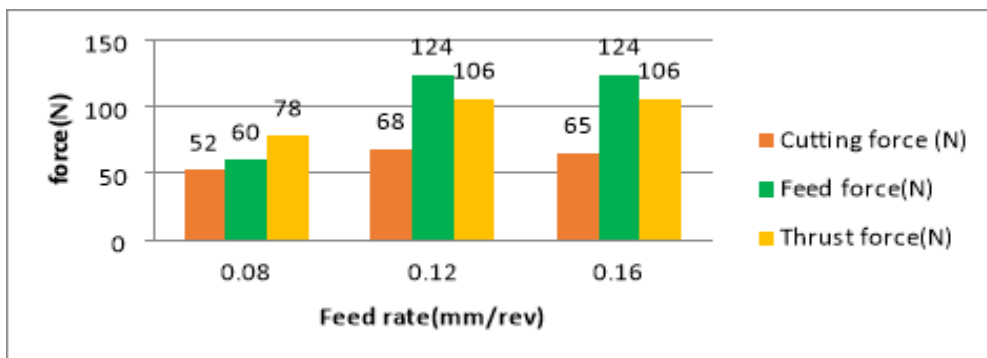


Figure 3: Feed rate Vs cutting force, feed force, and thrust force.
Source: Authors, (2026).

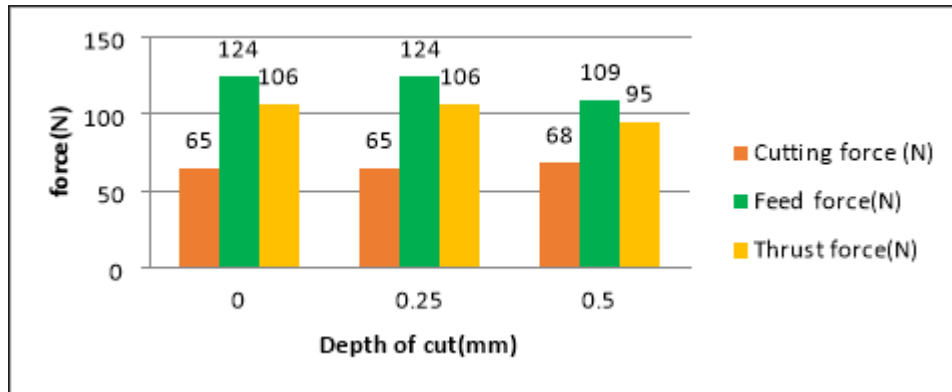


Figure 4: Depth of cut Vs cutting force, feed force, and thrust force.
Source: Authors, (2026).

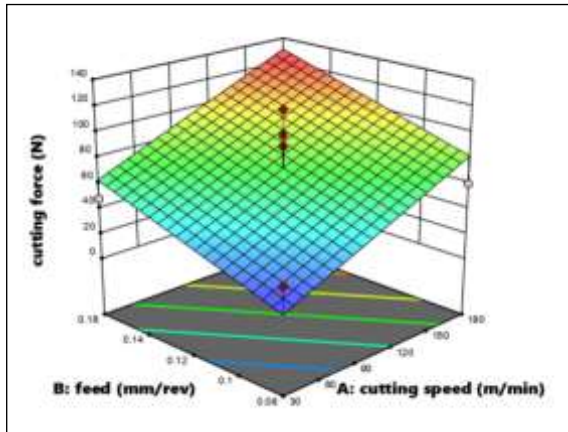


Figure 5: (a) Response surface plot illustrating how feed rate and cutting speed affect cutting force at a constant depth of cut.

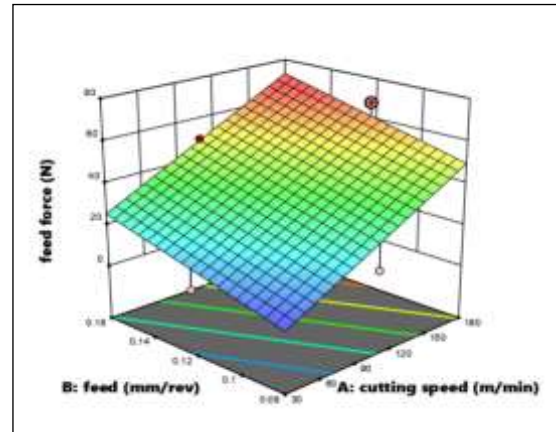


Figure 5: (b) Response surface plot illustrating how feed rate and cutting speed affect feed force at constant cut depth.

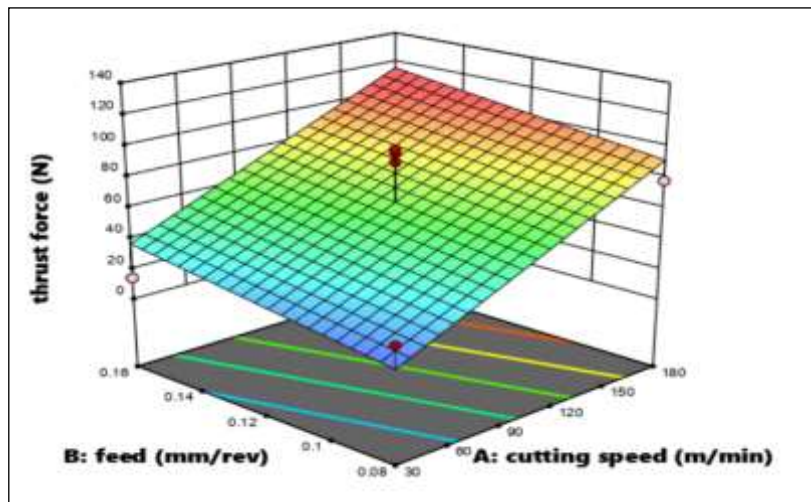


Figure 5: (c) Response surface plot illustrating how feed rate and cutting speed affect thrust force at constant cut depth.
Source: Authors, (2026).

The RSM 3D surface plots depicting the effects of cutting speed and feed rate on cutting force, feed force, and thrust force at a fixed depth of cut are shown collectively in Figure 5 (a–c). For all three responses, feed rate emerges as the most influential parameter, with forces increasing significantly as feed increases, while cutting speed exhibits a secondary but noticeable effect, particularly at higher feed levels. Minimum force values are obtained at lower cutting speed and feed combinations, whereas maximum forces occur at elevated parameter levels. The smooth and continuous response surfaces indicate strong interaction between cutting speed and feed, confirming the adequacy of the developed RSM models in predicting machining force responses [26–28]. The actual and predicted forces at the optimized condition are approximately feed force is 33.53 N, cutting force is 58.82 N, and thrust force is 57.78 N, as presented in Tables 5, 6, and 7, demonstrating a balanced and stable machining regime. The smooth contour trends and close agreement between experimental and predicted values confirm the adequacy of the developed RSM models for effective process optimization [29], [30].

Table 5: Experimental vs Predicted Cutting Forces and Errors.

Run	Cutting force	Predicted	Error%
13	58	57	1.75

Source: Authors, (2026).

Table 6: Experimental vs Predicted Feed Forces and Errors.

Run	Feed force	Predicted	Error%
15	34	33.53	1.40

Source: Authors, (2026).

Table 7: Experimental vs Predicted Thrust Forces and Errors.

Run	Thrust force	Predicted	Error%
16	60	57.78	3.84

Source: Authors, (2026).

V. CONCLUSIONS

- Machining parameter influences the Feed rate and depth of cut are the primary factors affecting cutting, feed, and thrust forces, while cutting speed exhibits a secondary but statistically significant influence.
- Force variation trends in the cutting, feed, and thrust forces increase with higher feed rates and greater depths of cut due to increased uncut chip thickness and shear plane engagement.
- Effect of higher cutting speeds influences the moderate increase in force components as a result of enhanced tool–chip friction and strain-rate sensitivity of the work material.
- Stable machining region based on Minimal force values are observed at low cutting speed–low feed–low depth combinations, representing stable and energy-efficient machining conditions.
- Model adequacy shows that Quadratic regression models developed using Response Surface Methodology (RSM) accurately predicts machining forces as functions of cutting speed, feed rate, and depth of cut.
- Statistical validation gives ANOVA results confirm model significance (F-values ranging from 8.84 to 10.05) and non-significant lack-of-fit values, ensuring strong predictive reliability.
- Optimization outcome shows the predicted optimum forces—33.53 N (feed force), 58.82 N (cutting force), and 57.78 N (thrust force)—demonstrate a balanced, stable, and efficient machining regime.
- The optimized machining conditions reduce tool loading, power consumption, and vibration levels, thereby improving tool life and surface finish.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: S.Vani and T. Ebesu.

Methodology: S. Vani and M.Reddeiah.

Investigation: S.Vani and S.Vikranth Deepak.

Discussion of results: S. Vani, Reddeiah and S.Vikranth Deepak.

Writing – Original Draft: S.Vani.

Writing – Review and Editing: S.Vani and T.Ebesu.

Resources: M.Reddeiah.

Supervision: M.Reddeiah and S. Vikrath Deepak.

Approval of the final text: S.Vani, M.Reddeiah, S.Vikranth Deepak and T.Ebesu.

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