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PREDICTIVE MODELS FOR CUTTING FORCE IN TURNING TOOLS BASED ON RESPONSE SURFACE METHODOLOGY

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ABSTRACT

This paper presents the development of predictive models for feed cutting force component when turning mild steel rods at 90owith cutting tools in a local lathe shop. The predictive models were formulated with cutting condition kept dry. Experimental plan was based on Rotatable Central Composite Design (RCCD) and cutting forces generated in the feed direction was measured using a dynamometer. Analysis was performed on the generated data for both tool-work piece combination and feed rate and its squared effect is found to influence the response variable greatly. However, other factors and their interactions provide secondary contributions. Next, the predicted models were compared with the measured feed cutting forces and an agreement established. The coefficient of determination R^2 values of the models gave 76% and 79% respectively, which indicate that the predicted models could adequately describe the process within the conditions that were being studied.

Contribution/Originality: This study contributes in the existing literature by proffering simplistic and cost effective cutting force model based on a planned experiment and statistical methodology.

1. INTRODUCTION

The idea of cutting forces produced during turning operation under given cutting conditions is of great importance to machinists, being an important criterion for material machinability. Also, their prediction helps in the analysis of optimization problems in machining economics, control applications and in the formulation of models used in cutting databases. An accurate prediction of the cutting forces depends on the empirical modelling of cutting forces. Also in turning, cutting forces have been found to be influenced by a number of factors or variables like cutting time, workpiece hardness, etc. (Thomas and Beauchamp, 2003). In order to effectively model cutting forces during machining studies, statistical Design of Experiments is often used. Statistical Design of Experiments refers to the process of planning the experiment so that the appropriate data can be analyzed by statistical methods (Montgomery, 2003). There are various experimental designs used by researchers to plan their experiments they include; Central Composite Design (CCD) (Cukor *et al.*, 2011; Ihueze *et al.*, 2013; Ihueze and Okafor, 2014; Guyo *et al.*, 2017) factorial design (Pandis *et al.*, 2013; Ihueze *et al.*, 2017; Snetsinger and Alkhatib, 2018) and Taguchi methods (Ihueze *et al.*, 2012; Okafor *et al.*, 2013; Arefi *et al.*, 2017). They are now widely used in place of one-factor-at-a-time experimental approach which is time consuming and exorbitant in cost.

Also, Response Surface Methodology commonly abbreviated as RSM is used for empirical modeling. It analyzes a planned experimental data statistically to arrive at valid and objective conclusions. In RSM, process parameters can be represented quantitatively as

$$Y = f(X_1, X_2, X_3 \dots \dots X_n) \pm \varepsilon \qquad (1)$$

Where, Y is the response variable, f is the response function, ε is the error term and $X_1, X_2, X_3 \dots \dots X_n$ are independent variables. By plotting the response Y against the independent variables or predictors a surface known as the response surface is generated. If the response can be well modeled by a linear function of the independent variables, equation (1) can be rewritten as

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 \dots \dots C_nX_n \pm \varepsilon \qquad (2)$$

However, if a curvature appears on the plot, then a higher order polynomial is formed and it is given as

$$Y = C_0 + \sum_{i=0}^{n} C_iX_i + \sum_{i=0}^{n} C_{ii}X_i^{\,2} + \sum_{i<j}^{n} C_{ij}X_iX_j \pm \varepsilon \qquad (3)$$

Cutting forces as a response variable of a machining system has over the years been studied by researchers in various cutting processes through formulation of models for their estimation. The development of empirical models for cutting forces has received considerable attention from researchers like Kienzle and Victor (1957); Tlusty (2000); Kurt *et al.* (2010) etc. Kurt *et al.* (2010) experimentally investigated cutting forces which occurred during metal cutting, analyzed the effects on tools by means of ANSYS software and mathematically modeled the primary cutting force and the stresses using the acquired findings. Feng and Menq (1994) used dynamometer to measure experimental cutting forces and analytically fitted the force model. They designed a 2-D cutting force model, without considering cutting force along the axis of the cutting tool. Yang and Tarng (1998) used the Taguchi method for turning operations to find the optimal machining parameters. Wassila (2005) minimized the production time in high speed turning by optimizing cutting parameters.

Some of the researchers mentioned above have actually performed studies on modeling of cutting forces and as well optimized the process of turning, effort will be made in this study to simplify and adopt these modeling techniques in order to solve a local problem in lathe shops. These models will be formulated in dry orthogonal turning condition and cutting parameters. RCCD will be used to plan the experiments and analysis will be done using RSM to ascertain factors that influences cutting forces. Next, comparison will be done between the models and the measured feed cutting forces to establish agreement.

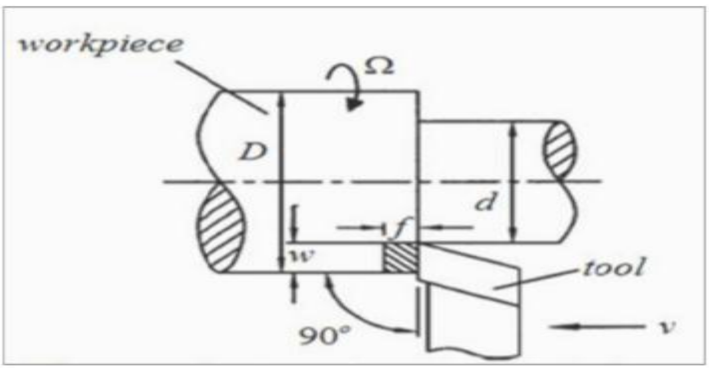

Figure-1. Turning process showing cutting parameters
Source: Youssef and El-Hofy (2008)

2. EXPERIMENTAL DETAILS

2.1. Materials

The materials used for the experiment are carbide tools brazed on a flexural steel shank and High Speed Steel tools with dimensions $100mm \times 12mm \times 12mm$ respectively. The choice of these two cutting tools lies on their application in local lathe shops. Mild steel rod sample of $35mm$ diameter and $280mm$ long was used as the workpiece.

Figure-2. Material and cutting tools used during turning test

Source: Ezeanyagu (2017)

2.2. Method

In this particular study, turning process was studied using RCCD to select cutting parameters at $n = 3$ factors. For the CCD the rotation criterion is given by equation (4) as

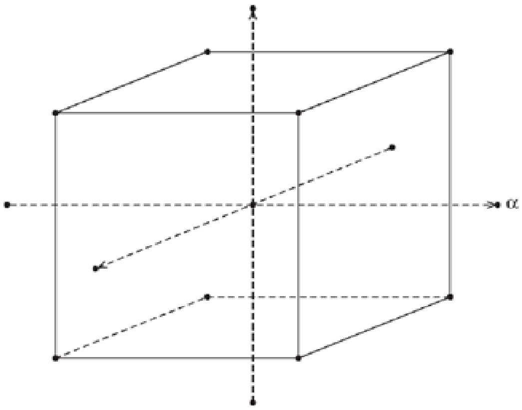

Figure-3. CCD with rotation

Source: Ezeanyagu (2017)

$$\alpha = 2^{n/4} \tag{4}$$

Equation (4) gives $\alpha = \sqrt{3} = 1.682$ for $n = 3$, which is the same as the rotatable design with a number of replicate center points (points at the origin). Table 1 shows the experimental plan used for the study.

Table-1. Physical and coded values of factors in RCCD for both tool-workpiece combination

Symbol	Factors / Levels	Lowest	Low	Centre	High	Highest
	Coding for RCCD	-1.682	- 1	0	1	1.682
A	Spindle speed $(rpm) = \Omega$	90	370	660	950	1230
B	Feed $(mm/rev) = f$	0.076	0.22	0.36	0.50	0.64
C	Depth of cut $(mm) = w$	0.10	0.45	0.80	1.15	1.50

In this experimental plan, the required number of experimental runs is given by

$$N = 2^n + 2n + n_r \quad (5)$$

Eight factorial experiments with an additional 6 star points and centre point repeated 6 times (Jurkovic, 1999; Montgomery, 2003). Using equation (5), $N = 20$ is gotten as the required number of experimental runs.

Table-2. RCCD with 20 experimental runs

No. of Runs	*A*	*B*	*C*
1	- 1	- 1	- 1
2	1	- 1	- 1
3	- 1	1	- 1
4	1	1	- 1
5	- 1	- 1	1
6	1	- 1	1
7	- 1	1	1
8	1	1	1
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	- 1.682	0	0
16	1.682	0	0
17	0	- 1.682	0
18	0	1.682	0
19	0	0	- 1.682
20	0	0	1.682

Figure-4. Dry turning test and feed cutting force measurement using dynamometer

Source: Ezeanyagu (2017)

2.3. Setup and Experimentation

During turning test on the 4.0 kw Dean Smith & Grace lathe tool after the experimental plans, the workpiece was mounted, clamped on the spindle and machined at pre-defined spindle speeds, feed rates and depths of cut.

Turning tests involved 20 runs and its response variable the feed cutting force F_x generated on the clamped cutting tool was measured in Newton using a spring in-glass type dynamometer. In order to minimize the effect of tool wear, cutting tools were replaced after each cut in the test. The turning tests were devoid of coolant, making the turning test absolutely dry.

3. RESULTS AND DISCUSSION

3.1. Results

The results from the turning tests performed as per the RCCD were presented in Table 3 and 4 respectively.

Table-3. Feed cutting forces measured for carbide tool-mild steel pair with coded factors

N	*A*	*B*	*C*	F_x (*Newton*)
1	- 1	- 1	- 1	140.50
2	1	- 1	- 1	139.90
3	- 1	1	- 1	235.50
4	1	1	- 1	245.10
5	- 1	- 1	1	154.50
6	1	- 1	1	146.60
7	- 1	1	1	255.50
8	1	1	1	250.20
9	0	0	0	226.00
10	0	0	0	226.00
11	0	0	0	226.00
12	0	0	0	226.00
13	0	0	0	226.00
14	0	0	0	226.00
15	- 1.682	0	0	240.50
16	1.682	0	0	226.80
17	0	- 1.682	0	72.60
18	0	1.682	0	266.50
19	0	0	- 1.682	192.50
20	0	0	1.682	230.50

Table-4. Feed cutting forces measured for HSS tool-mild steel pair with coded factors

N	*A*	*B*	*C*	F_x (*Newton*)
1	- 1	- 1	- 1	124.50
2	1	- 1	- 1	121.00
3	- 1	1	- 1	216.50
4	1	1	- 1	220.00
5	- 1	- 1	1	130.50
6	1	- 1	1	132.00
7	- 1	1	1	138.20
8	1	1	1	239.50
9	0	0	0	208.00
10	0	0	0	208.00
11	0	0	0	208.00
12	0	0	0	208.00
13	0	0	0	208.00
14	0	0	0	208.00
15	- 1.682	0	0	203.50
16	1.682	0	0	200.00
17	0	- 1.682	0	46.00
18	0	1.682	0	246.50
19	0	0	- 1.682	188.40
20	0	0	1.682	221.60

3.2 Analysis of Variance

The statistical analysis software Minitab 17 was used to generate the regression coefficients of the proposed model in equation (3). The second-order relevant model for the feed cutting force F_x for both tool-workpiece combination respectively is as follows;

$$F_x = 18 - 0.175A + 867B + 108C + 0.347AB + 0.0958AC - 244BC - 0.000009A^2 - 826B^2 - 49.9C^2 \quad (6)$$

$$F_x = 11 - 0.133A + 888B + 31C + 0.329AB + 0.1266AC - 193\,BC - 0.000049A^2 - 885B^2 - 25.1C^2 \quad (7)$$

The models in equation (6) and (7) were tested for their adequacy using ANOVA and the influence of the factors on the variance is shown in Table 5 and 6 respectively.

Table-5. ANOVA table for Carbide tool-workpiece combination

Source of Variance	DF	SS	MS	F	P
Model	9	41149.9	4572.2	6.90	0.003
Linear	3	30601.3	10200.4	15.38	0.000
A	1	274.4	274.4	0.41	0.535
B	1	30289.3	30289.3	45.68	0.000
C	1	37.6	37.6	0.06	0.817
Square	3	7242.0	2414.0	3.64	0.052
A^2	1	12.7	12.7	0.02	0.893
B^2	1	6780.8	6780.8	10.23	0.010
C^2	1	941.2	941.2	1.42	0.261
2-Way Interaction	3	3489.5	1163.2	1.75	0.219
AB	1	1590.5	1590.5	2.40	0.152
AC	1	756.6	756.6	1.14	0.311
BC	1	1142.4	1142.4	1.72	0.219
Error	10	6631.2	663.1	-	-
Total	19	47781.1	-	-	-

Note: DF = Degree of freedom; **SS** = Sum of squares; **MS** = Mean squares; **F** = F-value; **P** = P-value.

Table-6. ANOVA table for HSS tool-workpiece combination

Source of Variance	DF	SS	MS	F	P
Model	9	43262.7	4807.0	8.26	0.001
Linear	3	32196.0	10732.0	18.45	0.000
A	1	548.8	548.8	0.94	0.354
B	1	31602.4	31602.4	54.32	0.000
C	1	44.8	44.8	0.08	0.787
Square	3	7793.2	2597.7	4.47	0.031
A^2	1	406.5	406.5	0.07	0.423
B^2	1	7776.1	7776.1	13.37	0.004
C^2	1	237.9	237.9	0.41	0.537
2-Way Interaction	3	3465.0	1155.0	1.99	0.180
AB	1	1425.8	1425.8	2.45	0.149
AC	1	1321.0	1321.0	2.27	0.163
BC	1	718.2	718.2	1.23	0.293
Error	10	5817.9	581.8	-	-
Total	19	49080.5	-	-	-

Note: DF = Degree of freedom; **SS** = Sum of squares; **MS** = Mean squares; **F** = F-value; **P** = P-value.

It is observed from Table 5that the greatest effect on the feed cutting force F_x is exhibited by *B*, followed by *A* and least for *C*. This is because *B* has the lowest P-value than *A* and *C*. The squared main factor is highest for B^2, followed by C^2 and least for A^2. Their interactions are less significant as *AC* shows the least contribution. Also, it is observed from Table 6 that the greatest effect on the feed cutting force F_x is exhibited by *B*, followed by *A* and least for *C*. This is because *B* has the lowest P-value than *A* and *C*. The squared main factor is also highest for B^2, followed by A^2 and least for C^2. Their interactions are less significant as *BC* shows the least contribution. Using the backward elimination of terms, setting P-value at 0.05, terms that are less significant to equation (6) and (7) such as *A*, *C*, *AB*, *AC*, *BC*, A^2 and C^2 are removed to enhance the models. The reduced quadratic models are shown in equation (8) and (9) respectively

$$F_x = 5.3 + 858B - 766B^2 \tag{8}$$

$$F_x = -22.3 + 905B - 822B^2 \tag{9}$$

3.3. Response Surfaces

The 3-D response surfaces for the feed cutting force models of equation (6) and (7) are depicted in figure 5-10. They have curvilinear arrangement in line with the reduced quadratic models.

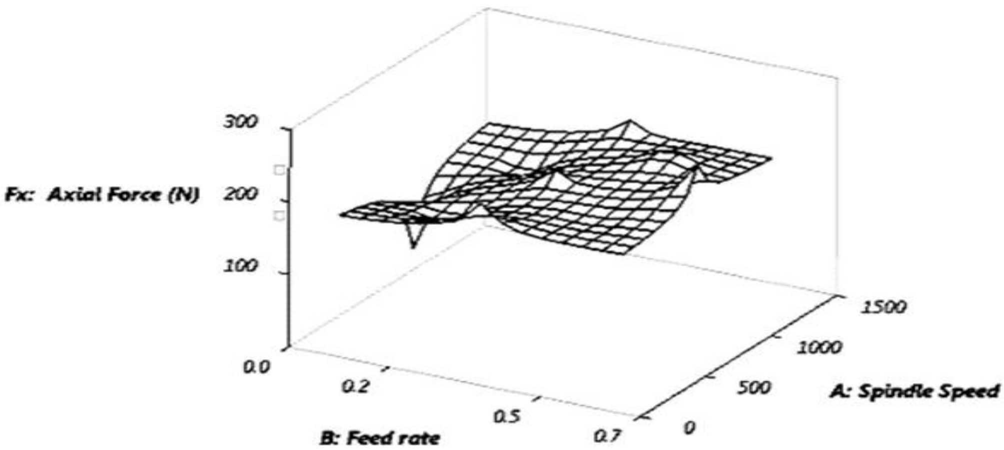

Figure-5. 3-D response surface for carbide tool-workpiece pair showing the interaction *AB*

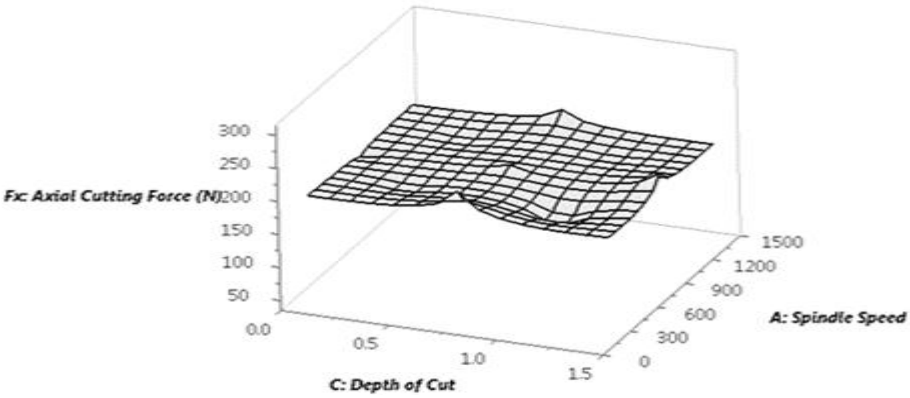

Figure-6. 3-D response surface for carbide tool-workpiece pair showing the interaction *AC*

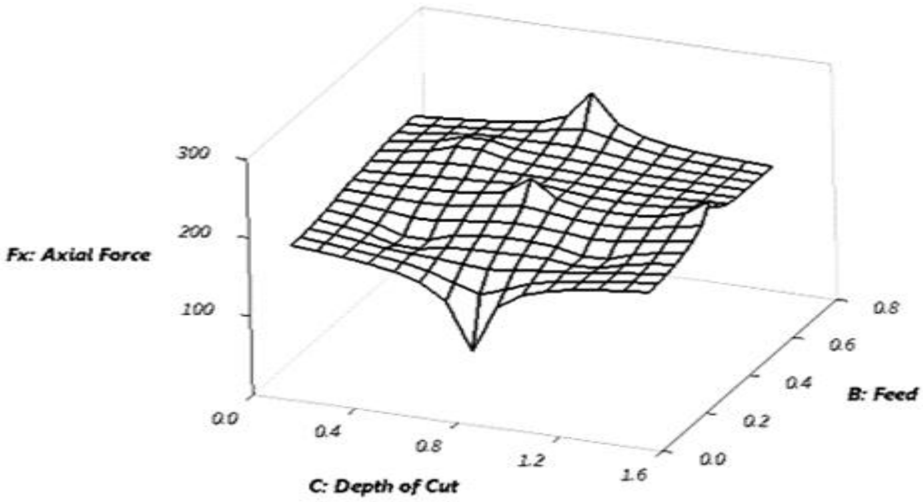

Figure-7. 3-D response surface for carbide tool-workpiece pair showing the interaction *BC*

The low curvilinear profile of the surface plot in figure 5-7 suggests that the interaction effects *AB*, *AC* and *BC* on the feed cutting force F_x for carbide tool-workpiece pair is reasonably small and conforms with the result gotten on Table 5.

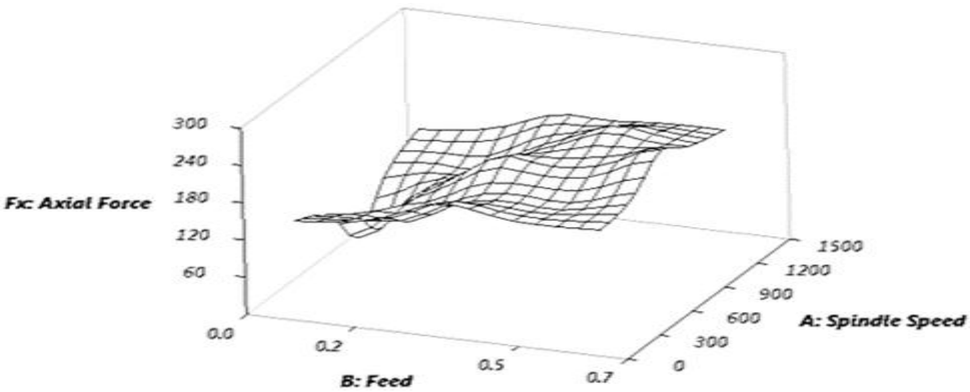

Figure-8. 3-D response surface for HSS tool-workpiece pair showing the interaction *AB*

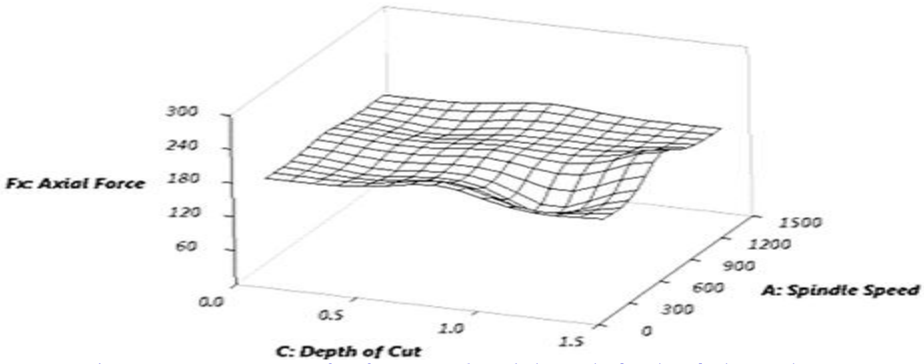

Figure-9. 3-D response surface for HSS tool-workpiece pair showing the interaction *AC*

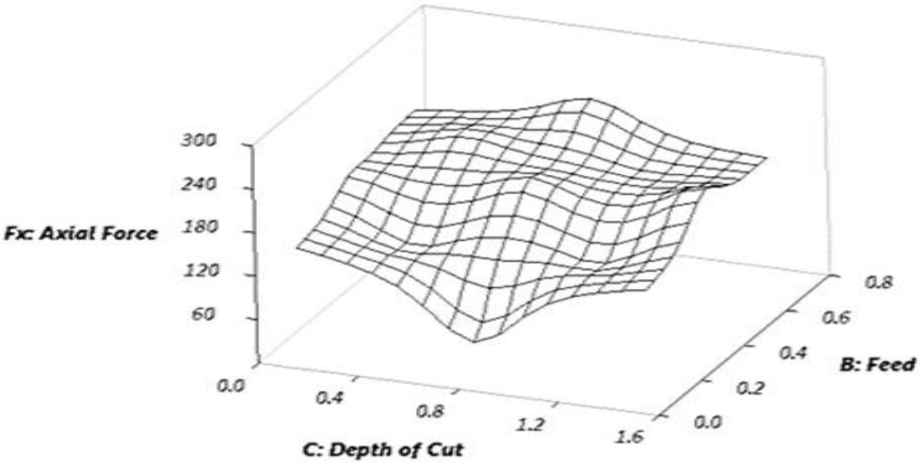

Figure-10: 3-D response surface for HSS tool-workpiece pair showing the interaction *BC*

Also, the low curvilinear arrangement of the surface plot in figure 8-10 suggests that the interaction effects *AB*, *AC* and *BC* on the feed cutting force F_x for HSS tool-workpiece pair is reasonably small and conforms with the result gotten on Table 6.

3.4. Validation of Proposed Models

The models in equation (8) and (9) generated for both tool-workpiece combinations respectively were validated by comparing their predicted force values in Newton with their measured values.

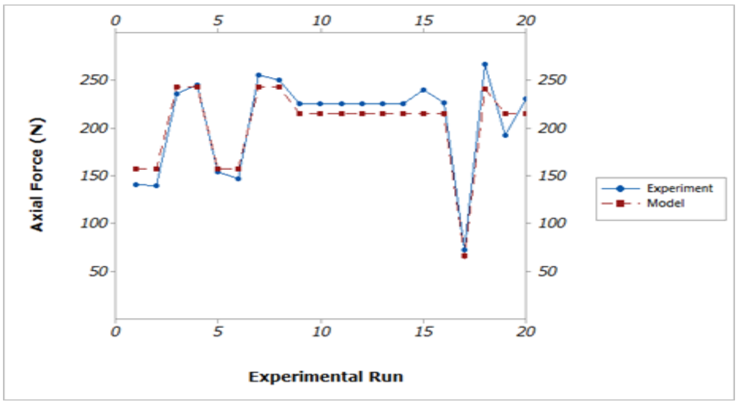

Figure-11. Comparison between measured and model for carbide tool-workpiece pair

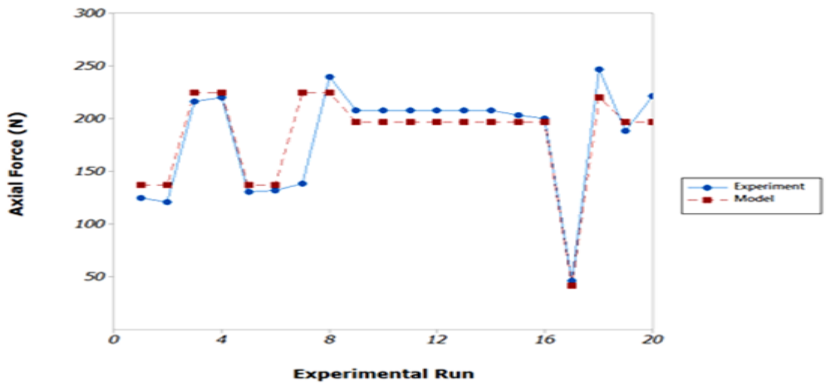

Figure-12. Comparison between measured and model for HSS tool-workpiece pair

The coefficient of determination R^2 values of the models in equation (8) and (9) were found to be 76% and 79% respectively, which suggests that the developed models are adequate.

4. CONCLUSION

This study shows a predictive model for feed cutting force determination when turning mild steel rod with carbide and HSS tools respectively. The results gotten using RSM revealed that the feed rate is the most significant factor that influences feed cutting force during turning operation. However, other factors like spindle speed and depth of cut provide secondary effects. Also, comparison was done between the models and the measured feed cutting forces and an agreement was established. The study indicate that the developed models adequately describe the process of turning.

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Contributors/Acknowledgement: All authors contributed equally to the conception and design of the study.

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