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Assessment of Cutting Force and Thrust Force in Lathe Orthogonal Turning of AISI-4140 Steel using Predictive Models

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ABSTRACT

In engineering industries, where shaping of material to its size and specifications is constantly embarked on, machining is an extreme fundamental activity. The three most important machining operations are turning, milling and drilling. Turning operations require machine tool called lathe, and to impart the desired quality and accuracy into any turned part requires the application of suitable single point cutting tool. Once the cutting tool and workpiece is established, the cutting force then determines the production rate. This study, thereby focused on the development of predictive force models in orthogonal turning of AISI-4140 steel. The effect of depth of cut, feed rate, cutting speed and tool noise radius in relation to the responses was also investigated. In the process, turning operations were performed and the main cutting force and thrust force were measured with a lathe dynamometer. Both regression analysis and analysis of variance were used for data analysis. The minimum cutting force measured and predicted were 173.110N and 173.015N, respectively. For thrust force, the minimum evaluated and predicted values were 77.207N and 70.897N, respectively. From the data, regression models for the dependent variables were developed using Minitab. Feed rate was found to predominantly impact on main cutting force and thrust force. The coefficient of determination. values for both main cutting force and thrust force were 98.10 % and 98.93%, respectively. Also, results showed a good agreement between both data, which justified the capability of the models to predict the expected forces in turning AISI 4140 steel. It was found that depth of cut affected main cutting force the most, while feed rate has more influence on thrust force. Regression model is an adequate for thrust force and main cutting force analyses in orthogonal turning of AISI-4140 in dry environment.

KEYWORDS: Orthogonal, Cutting Force, Depth of Cut, Feed Rate, Thrust Force

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1. INTRODUCTION

Presently, metal cutting is indeed a large area of industrial activities and the most often used method on conventional lathe is orthogonal. During orthogonal turning, the tool approaches the workpiece with its cutting edge parallel to the uncut surface at right angles to the direction of cutting. This type of machining, involved two perpendicular forces called main cutting force and thrust force. While the main cutting force acts in the direction of the cutting speed and take responsibility of cutting, the thrust force acts normally to it. The vectorially sum of these forces provide the energy needed for machining. The turning forces depends on tool nose radius workpiece material, feed rate, depth of cut and speed. These cutting forces could lead to reduced productivity, since lowered cutting speed could have negative effect on the surface integrity of the final products. The modeling of these forces is important, since it could be applied for economic of tool handling, energy evaluation and prediction of machining time.

Bhuiyan and Ahmed (2013) studied the relationship of main force and machining variables during turning on a conventional lathe machine with AISI 1040 specimen. In that study, MAPE, a genetic algorithm, and response methodology were employed for analysis. The data of the force equation developed compared to experimental results showed a good

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correlation. The results validated the fitness of the surface response model developed. Hanief and Charco (2017) used red brass to investigate the response of cutting force with varies cutting conditions in turning. The tool utilized were ANN, full factorial and regression analysis. Although, results showed that multiple regression models were able to predict the forces, artificial neural network was found to be more accurate. Raju *et al.* (2013) reported research on process variables and improvement of outputs was paramount. Two separate specimens (ferrous and non-ferrous) were turned on a center lathe. Regression models for cutting force and surface roughness were developed and analyzed using factorial technique and analysis of variance. The results of the models were found to be adequate for use for prediction of dependent variables. Daniel *et al.* (2014) also developed predictive models for forces in orthogonal cutting of carbon steel using computer numerical control lathe. The cut thickness, cutting speed, tool rake angle, and tool wear were the input variables selected. Based on analyzed results, wear of cutting tool was the most significant parameter that affected force components and thrust force.

Wayal *et al. (*2015) studied the influence of machining on force and vibration signals in turning operations. Mathematical model was formulated and analyzed using response surface methodology. Results revealed that vibration signals increased with cutting speed Chen *et al.* (2018) analyzed cutting response using AD730 as test specimen. The desired responses were cutting forces and surface integrity. Results revealed that forces increased with feed rate, but appreciation in speed reduced machining forces and surface integrity. Rahul-Kshetri (2018) carried out a study on modeling and analysis of forces in turning. The work material used was red brass. Force models were generated by the use of Minitab software. Surface plot was used for analysis. It was found

that depth of cut played a dominant role in affecting the forces. The mathematical models of the three force components were also found to be adequate as predictive models in turning red brass. Chandra and Kumar (2018) investigated the changes in cutting force and surface roughness when feed rate and cutting speed were varied in turning ISO 3685 on a center lathe. Similarly, Basmaci (2018) used feed rate, depth of cut and cooling systems to study surface roughness and cutting force behavior in a CNC orthogonal turning experiment using AISI 316L steel as work material. Taguchi principle was used for design, while ANOVA and Pareto principle were used for data analysis. The researcher concluded that feed rate mostly affected surface roughness and depth of cut influenced cutting force the most. Bani *et al.* (2022) investigated the optimal combination of tool nose radius and cutting variables for the overall performance for both AISI 4140 steel and IS-2062 steel. The both materials were machined on a center lathe and measurements were taken. The data collected was analyzed through grey relational analysis. Results showed that grey relational optimal interactions of machining parameters for the overall performance were: N_R (0.35mm), U_o (0.5mm), V_w (65m/min), R_f (0.2mm/rev) for both materials. Also, grey relational grade improved by 1.2767 (24.69%) for the expected optimal design for AISI-4140 steel, and improved by 1.7417 (33.68%) for the expected optimal design for IS-2062 steel. Grey relational analysis reduced the factors affecting the dependent variables to only two (feed rate and depth of cut).

The study seeks to develop predictive models for both main cutting force and thrust force in orthogonal turning of AISI-4140 steel and assess the effect of machining parameters on performance characteristics.

2. MATERIALS AND METHODS

2. 1 Materials

The composition by weight of AISI 4140 steel utilized in this study is depicted in Table 1 (Bani *et al.*, 2022). High-speed cutting tool is an alloy steel used to manufacture items like axles, conveyor parts, crowbars, gears, engines, logging parts, lathe spindles, drive shafts, sprockets, studs, pinions, pump shafts, ring gear, rams and connecting rods (Kus *et al.*, 2015; Sharan & Patel, 2019). High speed steel has a good balance of strength, toughness, and wear resistance because of its high alloy contents.

Table 1: Chemical Composition of AISI 4140 Steel

Constituent	Weight (%)
Carbon	0.38-0.43
Silicon	0.15
Manganese	0.75-1.00
Chromium	0.8-1.10
Molybdenum	0.15-0.25
Sulphur	0.04
Phosphorus	0.033
Iron	Balance

2.2 Methods

Design of experiment is one of the widely used approaches based on number of runs, factors, and responses in the experimental process. Taguchi method was used to plan the L_9 orthogonal array depicted in (Table 2). This technique is more consistent in the operating environment. It expresses the fact that not all factors that cause variability in a process can be controlled and are called noise factors. Taguchi technique also identifies the controllable factors that minimize the effect of the noise factors. In the process, the noise factors are manipulated to ensure variability, thereby determine optimal control factor setting that make the process resistant to variation from the noise factors. Each test was replicated at three setting as follows: Tool nose radius (N_R), 0.15mm, 0.25mm, 0.35; Depth of cut (U_o), 0.5mm, 0.7mm, 0.9mm; Cutting speed (V_w), 65m/min, 83m/min, 101mm; and Feed rate (R_f), 0.2mm/rev, 0.3mm/rev, 0.4mm/rev, in order to achieve more reliable results.

Table 2: L_9 Populated Array of Taguchi Design

Experimental Runs	V_w	R_f	N_R	U_o
1	1	1	1	1
2	2	2	1	2
3	3	3	1	3
4	2	3	2	1
5	3	1	2	2
6	1	2	2	3
7	3	2	3	1
8	1	3	3	2
9	2	1	3	3

2.3 Machining Test Procedure

A workpiece specimen (AISI 4140 steel) of length 180mm and diameter 60mm was held with a three-jaw chuck and tailstock center of a conventional lathe. The cutting treatments were performed with high-speed steel tool fitted in a multi-tool post. During turning, the uncut part of specimen just ahead of the cutting tool edge is subject to a high compressive force; and this resulted in the development of shear stress at that region. When the shear stress approaches the magnitude of the shear strength of the specimen material, yielding occurs, resulting in plastic deformation and shearing off. This process continues with chips removal. Consequently, the formation of stresses on the tool face result to cutting force and thrust force. These two perpendicular forces were then measured with a lathe tool dynamometer (of the piezoelectric type) and readings were taken. The use of mathematical models is essential in predicting responses for any input data within the experimental domain. The data acquired was then utilized to form the equations of the two perpendicular forces using Minitab 16 software.

2.4 Models Development

In this study, multiple regression models were developed via Minitab 16 software. The models relate performance characteristics (dependent variables) and the machining independent variables. The models contains both linear and

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interactive terms as given in Equation (1) (Betiku *et al.*, 2014; Badom & Akpodee, 2020).

$$G = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_{11} X_1 X_1 + \ldots + \beta_9 X_4^2 + \varepsilon \quad (1)$$

where, G stands for the performance characteristics, $X_1, \ldots, X_n$ are the control parameters $\beta_o, \beta_1, \beta_2 \ldots \beta_n$ are estimators or coefficients to be computed from the experimental data obtained, and ε stands for the random error which accounts for the failure of the model to fit the data exactly. In this study, the independent variables are cutting speed (V_W), feed rate (R_r), depth of cut (U_o), and tool nose radius (N_R), while G is the dependent variables (main cutting force and thrust force). In order to formulate the models, the real machining parameters were inserted in Equation (1).

3. RESULTS AND DISCUSSION

3.1Analysis of Main Cutting Force

The outcomes of the tests performed are reported in Figure 1. The keys used for easy interpretation are defined as stated. The plot showed that the main cutting force increased continuously in magnitude as the feed rate increased. Volume of metal removed also increased with increased feed rate, since the work-piece resisted the rupture more and required large efforts for chip removal. It was found that cutting force decreased gradually as cutting speed increased. The decrease in cutting force is because the turned zone gained more heat and become more plastic, thereby rendering the cutting force required for shearing to decrease. Further observation revealed that cutting force reduced with increment in nose radius regardless changes in cutting speed. Obviously, low nose radius is required for orthogonal turning. Besides, a small nose radius ensures a sharp cutting edge of tool, hence, less cutting force is needed. Cutting force increased as depth of cut and feed rate increased. However, cutting force decreased to its minimum value when cutting speed and nose radius increased, but later remained approximately steady beyond the middle level of the control factors. This observed trend implies that in orthogonal turning of AISI-4140 steel material, there is no reason to increase the tool nose radius above 0.25mm and cutting speed beyond 83 m/min, within the limits of this study.

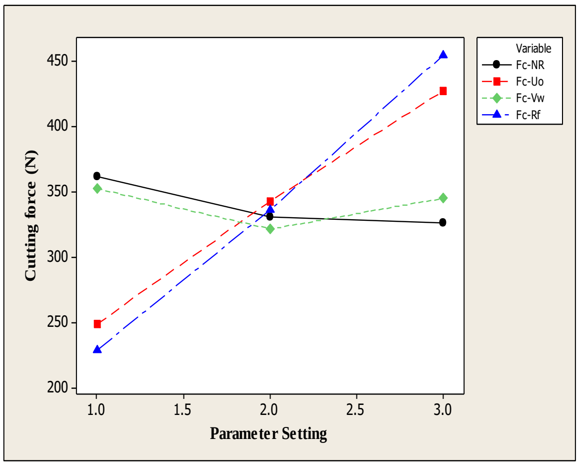

Figure 1: Cutting Force Versus Machining Parameters for AISI-4140 Steel.

Key: Fc-N_R: Cutting force due to tool nose radius, Fc-U_o: Cutting force due to depth of cut, Fc-V_W: Cutting force due to cutting speed, Fc-R_f: Cutting force due to feed rate

The output of the models relating predictors (tool nose radius, depth of cut, feed rate and cutting speed) and the main cutting force (Fc) and thrust force (Ft) respectively, are shown:

$$Fc = -187.274 + 2310.42\, N_R + 459.301\, U_o - 5.70954\, V_w + 809.427\, R_f - 2704.87 N_R U_o - 5.48976\, N_R V_w + 7.6831\, U_o V_w$$

$$F_t = -132.114 + 972.667\, N_R + 117.301\, U_o - 0.167288\, V_W + 337.59\, R_f - 619.514 N_R U_o - 6.97373\, N_R V_W + 1.92512\, U_o V_W$$

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The ANOVA results for main cutting force is presented in Table 3 and the headings are explained as follows: DF is the degree of freedom; SSS is the sequential sum of squares and represent the total variability in the observed data; ASS represent the adjusted sum of squares; AMS is the adjusted mean of squares; P is the probability statistics and U is the contribution of each component in percentage. The adequacy and accuracy of the main cutting force model was tested statistically at 0.05 % level of significance. The analysis of variance results in Table 3, illustrates the contributions and influence of each machining parameter as well as their two-way interactions in the main cutting force model developed. The results showed that main parameters and their interactions were significant, except the interaction of tool nose radius and cutting speed, whose p- value is greater than 0.05. It was also shown that feed rate and depth of cut contributed 59.75 % and 37.19 %, respectively on the main-cutting force. Also, the coefficient of determination (98.10 %) obtained revealed a high significance of the cutting force model for turning AISI-4140 steel specimen.

Table 3: Analysis of Variance Results of Main Cutting Force for AISI 4140 Steel.

Source	DF	SSS	ASS	AMS	P	U %
Regression	7	128065	128065	18295.0	0.0060765	
N_R	1	1878	804	803.7	0.0239591	1.47
U_o	1	47629	649	648.6	0.0266680	37.19
V_W	1	79	319	319.1	0.0379942	0.06
R_f	1	76522	5616	5615.8	0.0090676	59.75
N_RU_o	1	462	1707	1707.1	0.0164434	0.36
N_RV_W	1	602	57	57.0	0.0894476	0.47
U_oV_W	1	893	893	892.5	0.0227367	0.70
Error	1	1	1	1.1		
Total	8	128066				

Coefficient of Determination, R^2 = 98.10 %

More still, both measured and predicted data of main cutting force were plotted against the number of experimental runs as illustrated in Figure 2. Figure 2, reveals that a strong correlation exists between the experimental and predicted data, which is an indication of the fitness of the model to predict the main cutting force in turning AISI-4140 steel.

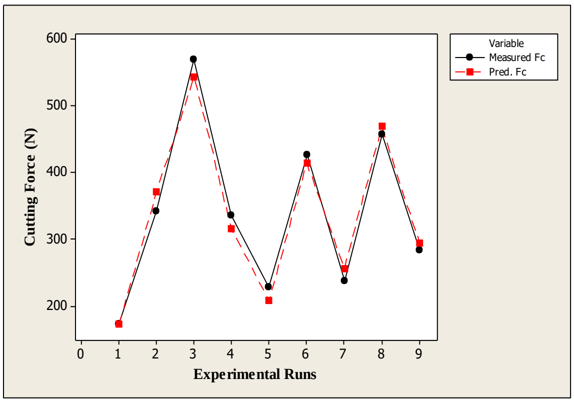

Figure 2: Measured F_c, Predicted F_c Versus Expt. Runs for AISI-4140 Steel.
Key: Measured, Fc = Main Cutting Force
Measured Pred, F_c = Main Cutting Force Predicted

3.2 Analysis of Thrust Force

In orthogonal manufacturing using AISI-4140 steel specimen, thrust force was measured with lathe tool dynamometer at the workpiece-tool interface. The results were plotted against the parametric setting as presented in Figures 3. The keys used for easy interpretation are defined as stated. Figure 3, indicates that as feed rate increased, thrust force also increased. Similarly, thrust force was found to appreciate as depth of cut increased. Also, thrust force first reduced, then remained steady with increasing tool nose radius, however, with increased cutting speed, thrust force diminished, then later increased.

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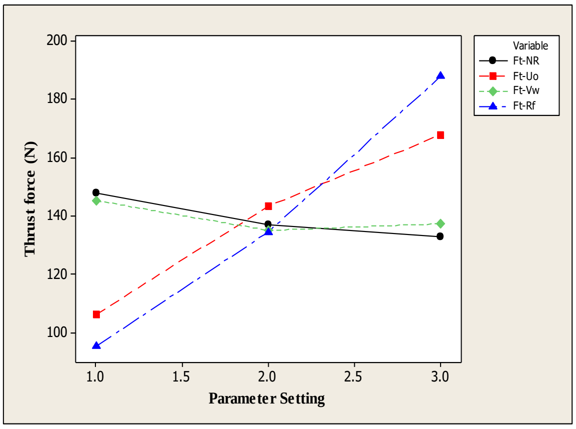

Figure 3: Thrust Force due to Machining Parameters for ISI-4140 Steel.

key: Ft-NR=Thrust force due to tool nose radius, Ft-Uo=Thrust force due to depth of cut, Ft-Vw= Thrust force due to cutting speed, Ft-Rf=Thrust force due to feed rate,

The data was analyzed using ANOVA and the results for main cutting force is presented in Table 4. Headings of Table 4 are explained as follows: DF is the degree of freedom; SSS is the sequential sum of squares and represent the total variability in the observed data; ASS is the adjusted sum of squares; AMS is the adjusted mean of squares; P is the probability statistics and U is the percentage contribution of the various components of the model developed. The adequacy and reliability of the thrust force model was examined at 95% level of confidence. The contributions of the machining parameters and their two-way interactions were also obtained. Analysis of variance results reported in Table 4 shows that feed rate contributed 66.83%, followed by depth of cut which contributed 29.5%. The contributions of tool nose radius and cutting speed were minimal. The combination of tool nose radius and cutting speed contributed 1.15% to the model. It was also found that all the main parameters, except cutting speed, contributed significantly to the thrust force model. The high coefficient of determination also shows a high degree of precision with which the experimental and predicted data of the thrust force are compared, hence, the model is valid for prediction of thrust force in orthogonal turning of AISI-414 steel.

Table 4: Analysis of Variance Results of Thrust Force for AISI- 4140 Steel.

Source	DF	SSS	ASS	AMS	P	U%
Regre	7	19188.9	19188.9	2741.27	0.002872	
N_R	1	332.7	142.4	142.44	0.010415	1.73
U_O	1	5661.5	42.3	42.30	0.019108	29.50
V_W	1	93.2	0.3	0.27	0.227327	0.49
R_f	1	12823.6	976.86	976.86	0.003978	66.83
N_RU_O	1	0.7	89.0	89.55	0.013135	0.00
N_RV_W	1	221.2	91.9	91.92	0.012965	1.15
U_OV_W	1	56.0	56.0	56.04	0.016604	0.29
Error	1	0.20	0.20	0.04		
Total	8	19188.9				

Coefficient of Determination, R^2 = 98.93%

To further investigate the adequacy of the thrust force models developed, measured and predicted data were compared as presented in Figure 4. For clarity, the keys used are also defined as shown. in Figure 4 shows a good agreement between both data, with minimum errors. Hence, it has been justified that the model of thrust force developed can be utilized to predict thrust force in machining the material considered in this study.

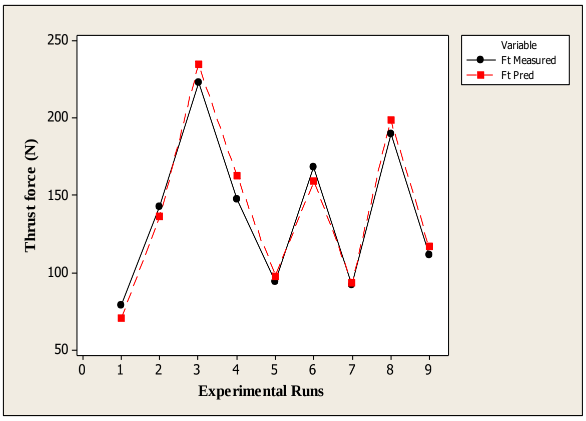

Figure 4: Measured Thrust Force, Predicted Thrust Force and Experimental Runs

Key: Ft Measured = Thrust Force measured Ft Pred.= Thrust Force Predicted.

4. CONCLUSION

In this study, cutting tests were performed on a lathe using AISI-4140 steel work piece material. The machining parameters were tool nose radius (N_R), depth of cut (U_o), feed rate (R_f) and cutting speed (V_w), while main cutting force (F_c) and thrust force (F_t) were the performance characteristics.

From results of analyses, the following have been reached:

i. Depth of cut affected the main cutting force the most, while feed rate has more influence on thrust force.

ii. Strong correlation exists between the experimental and predicted data, which indicates that both models can be used in predicting the desired performance characteristics in turning AISI-4140 work material.

iii. Regression model is adequate for thrust force and main cutting force analysis in orthogonal turning of AISI-4140 in dry environment.

NOMENCLATURE

AISI = American Institute of Streel and Iron
AMS = Adjusted Mean of Squares
ASS = Adjusted Sum of Squares
DF = Degree of Freedom
F_c = Cutting Force
F_t = Thrust Force
G = Dependent Variables
N_R = Tool Nose Radius
P = Probability Statistics
SSS = Sequential Sum of Squares
R_r = Feed Rate
U = Contribution of each Component in Percentage
U_o = Depth of Cut
V_w = Cutting Speed

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